# ANALYSIS OF POWER SYSTEM HARMONICS AND THEIR ELIMINATION USING FILTERS

by

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# ABSTRACT

The modern electric power systems that include non-linear loads may experience power quality problem such as harmonic distortion. Non-linear loads draw current that passes through all of the impedances between the loads and the system sources. The current causes power quality problems.

This thesis investigates the use of harmonic elimination methods to evaluate and improve harmonic distortion in the system. Computer simulation is used to determine the locations of the harmonics and the amount of the harmonic distortions. The results of the simulation are used to design filters for the various load locations and buses to improve power quality.

Short circuit ratio (SCR) at the point of common coupling (PCC) is to determine the current distortion limit (IEEE-519, 1992). The filters are applied to keep the total harmonic distortion (THD) of the current and the voltage within the limits set by the IEEE Recommended Practices and Requirements for Harmonic Control in electrical power systems.

For best result, filters are installed close to the non-linear loads. The application of the filters at the non-linear load locations reduce the total harmonic distortions of the voltage below 5 percent and the total harmonic distortions of the current below 15 percent. These limits meet the IEEE-519, 1992 limit.

# Contents

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Finally, I would like to dedicate this research work to my beloved parents whose blessings made this work a big success.

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# List of Acronyms and Symbols

| | |
|---|---|
| UPS | Uninterruptible Power Supply |
| SMPS | Switching Mode Power Supply |
| TNA | Transient Network Analyzer |
| NFRAP | Network Frequency Response Analysis Program |
| EPRI | Electrical Power Research Institute |
| MEHAP | McGraw-Edison Harmonic Analysis Program |
| PC | Personal Computer |
| IREQ | Institute de Recherche d'Hydro-Qubec |
| EMTP | Electromagnetic Transients Program |
| HVDC | High Voltage Direct Current |
| SCR | Short Circuit Ratio |
| DF | Distortion Factor |
| THD | Total Harmonic Distortion |
| RMS | Root Mean Square |
| KVA | Kilovoltampere |
| MVA | Megavoltampere |
| KVAR | Kilovoltampere Reactive |
| MVAR | Megavoltampere Reactive |
| KW | Kilowatt |
| MW | Megawatt |
| Tanδ | Loss Factor in Capacitor Bank |

| | |
|---|---|
| $\omega$ | Angular frequency |
| TIF | Telephone Influence Factor |
| ISC | Short Circuit Current |
| PCC | Point of Common Coupling |
| TDD | Total Demand Distortion |
| PB | Pass Band |
| $\Omega$ | Ohm |
| $1\Phi$ | Single-Phase |
| $3\Phi$ | Three-Phase |
| $V_{LL}$ | Line-to-Line Voltage |
| $V_{LN}$ | Line-to-Neutral Voltage |
| SVC | Static Var Compensators |
| PF | Power Factor |
| PTW | Power Tools For Windows |
| ASCII | American Standard Code for Information Interchange |
| HI_WAVE | Harmonic Investigation, Wave Analysis and Voltage Evaluation |

# Chapter I

## Harmonic Distortion and Effects of Harmonics

### 1.1 Introduction

In case of ideal power systems, the voltage supplied to customer equipment and the resulting load current are perfect sine waves. However, in practice, conditions are never ideal and waveforms are often distorted. This distortion or deviation from ideal is expressed in terms of harmonic content of the voltage and the current waveforms.

Sinusoid distortion normally occurs in multiples of fundamental frequency. In a 60 Hz power system, harmonic wave is a sinusoid which has a frequency given by

$$F_{\text{harmonics}} = n * 60\text{ Hz} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.1)$$

where, n is an integer.

Harmonics are characterized by a harmonic distortion factor (DF) given by

$$DF = (\text{Sum of squares of harmonic amplitudes/amplitude of the fundamental})^{1/2} \ldots\ (1.2)$$

This distortion factor characterizes distortion in both current and voltage waves.

### 1.2 Total Harmonic Distortion

The representation of harmonic current or voltage with respect to the fundamental is called total harmonic distortion (THD).

Total harmonic distortion of either current or voltage is given by

$$THD = 100\ (\textstyle\sum^{n}_{2} U_n^{2}\ )^{1/2} / U_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.3)$$

where, n is an integer and n = 2,3,4.......n. $U_1$ is the fundamental component of the signal and $U_2$ to $U_n$ are the harmonic components.

Total harmonic distortion of current is given by

$$I_{THD}\% = (I_3{}^2 + I_5{}^2 + I_7{}^2 + I_9{}^2 + \ldots\ldots.)^{1/2} / I_1\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.4)$$

where,

$I_1$, $I_3$, $I_5$, $I_7$, $I_9$,.....are the currents at their respective harmonics.

Similarly, total harmonic distortion of voltage is given by

$$V_{THD}\% = (V_3{}^2 + V_5{}^2 + V_7{}^2 + V_9{}^2 + \ldots\ldots.)^{1/2} / V_1\ \% \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.5)$$

where,

$V_1$, $V_3$, $V_5$, $V_7$, $V_9$,.....are the voltages at their respective harmonics.

## 1.3 Effects of Harmonics in Static Power Plant

The effects of harmonics can be clearly observed in the following power system components:

1. Transmission lines
2. Transformers
3. Capacitor banks

### 1.3.1 Effects on Transmission Lines

One of the two main effects produced by harmonic currents in a network is the additional transmission loss caused by the increased r.m.s. value of the current waveform. Transmission loss is given by

$$\text{Transmission loss} = \sum^{\infty}_{n=2} I^2_n R_n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.6)$$

where, n is an integer and n = 2,3,4......∞. $I_n$ is the *n*th harmonic current and $R_n$ is the system resistance at that harmonic frequency.

Creation of harmonic voltage drops across various circuit impedances is the second effect of the harmonic current flow. This effect can be expressed as a system with a large impedance (low fault level) and results in greater voltage disturbances than a system with a high fault level and low impedances. The effects of harmonics on corona starting and extinction level are functions of peak to peak voltage. The peak voltage depends on phase relationship between the harmonics and fundamental.

### 1.3.2 Effects on Transformers

The presence of harmonic voltages increases the hysteresis and eddy current losses and stresses the insulation. The flow of harmonic current increases the copper losses; this effect is more important in the case of convertor transformers because they do not benefit from the presence of filters, which are normally connected on the a.c. system side.

An important effect of harmonic currents is the circulation of triplen zero sequence currents in the delta windings of the power transformer. If a load current contains a d.c. component, the resulting saturation of the transformer magnetic circuit greatly increases the level of all harmonic components of the a.c. excitation current. Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Harmonic distortion of the current, in particular, as well as the voltage will contribute significantly to additional heating.

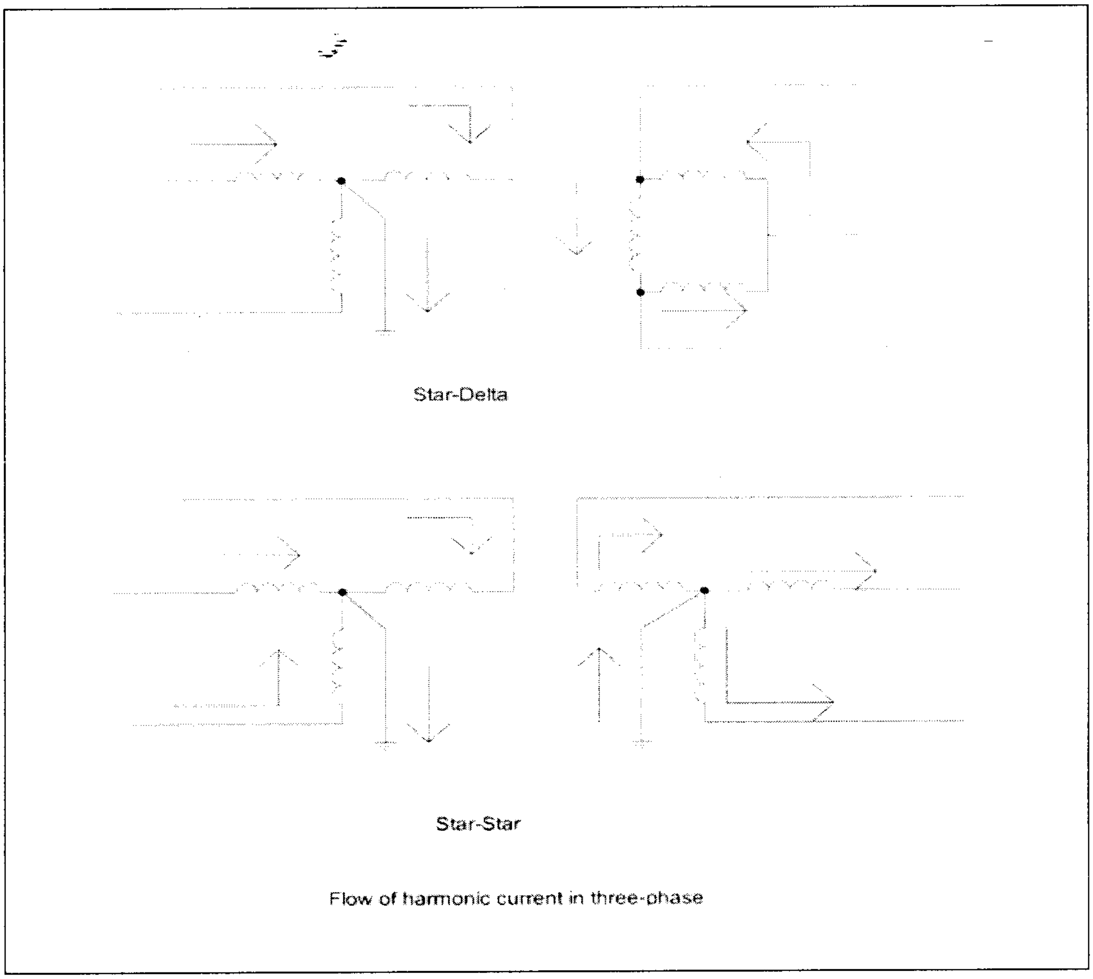


Figure 1.1. Flow of harmonic current in three-phase transformer.

There are three effects that result in increased transformer heating when the load current includes harmonic components:

1. R.M.S. current: If a transformer is sized only for the kVA requirements of the load, harmonic currents may result in the transformer r.m.s. current being higher than its capacity. The increased total rms current results in increased conductor heating.

2. Eddy-current losses: These are induced currents in a transformer caused by magnetic fluxes. These induced currents flow in the winding, in the core, and in other conducting bodies subjected to the magnetic field of the transformer and cause additional heating. This component of the transformer losses increases with the square of the frequency of the current causing the eddy currents.

3. Core losses: The increase in core losses in the presence of harmonics will be dependent on the effect of the harmonics on the applied voltage and the design of the transformer core. Increasing the voltage distortion may increase the eddy currents in the core laminations. The net impact that will have depends on the thickness of the core laminations and the quality of the core steel. The increase in these losses due to harmonics is generally not as critical as r.m.s. and eddy-current.

### 1.3.3 Effects on Capacitor Banks

The presence of voltage distortion produces an extra power loss in capacitors.

The extra loss in capacitor is given by

$$\text{Power loss} = \sum^{\infty}_{n=1} C\,(\tan\delta)\omega_n V_n^2 \text{..........................} \quad (1.7)$$

where, n is an integer and $n = 1,2,3....\infty$. $\tan\delta = R/(1/\omega C)$ is the loss factor, $\omega_n = 2\pi f_n$ and $V_n$ is the r.m.s. voltage of the *n*th harmonic. The total reactive power, including fundamental and harmonics given by

$\sum^{\infty}_{n=1} Q_n$ should not exceed the rated reactive power.

Series and parallel resonances between the capacitors and the rest of the system can cause overvoltages and high currents thus increasing the losses and overheating of capacitors and often lead to their destruction.

## 1.4 Effects of Harmonics on Rotating Machine

Harmonic voltages or currents cause extra losses in the rotor circuits and stator windings as well as in the stator and rotor laminations. The losses in the stator and rotor conductors are greater than those associated with the d.c. resistance because of the eddy current and skin effect. Harmonic currents set up leakage fields in the stator and rotor end windings which produce extra losses.

Motors can be significantly impacted by the harmonic voltage distortion. In case of the induction motors with skewed rotors, the flux changes in both stator and rotor and high frequency may result in the substantial iron loss. Harmonic voltage distortion at the motor terminals is translated into harmonic fluxes within the motor. Harmonic fluxes do not contribute significantly to motor torque, but rotate at a frequency different than the rotor synchronous frequency, basically inducing high-frequency currents in the rotor. The effect on motors is similar to that of negative sequence currents at fundamental frequency. Decreased efficiency, heating, vibration, and high-pitched noises are symptoms of harmonic voltage distortion.

At harmonic frequencies, motors can usually be represented by the blocked rotor reactance connected across the line. The lower-order harmonic voltage components, for which the magnitudes are the apparent motor impedance, are usually the most important for motors.

There is usually no need to derate motors if the voltage distortion remains within IEEE Standard 519-1992 limits of 5 percent THD and 3 percent for any individual harmonic. Excessive heating problems begin when the voltage distortion reaches 8 to10 percent and higher. Such distortion should be corrected for long motor life.

# Chapter II

# Problems Created by Harmonics

## 2.1 Introduction

Harmonic currents created by a convertor can flow into any part of ac system. When a resonant circuit exists anywhere in the system at or near the frequency of the harmonic currents, these currents will excite the resonant circuits, producing large oscillation that can overload protective devices causing them to fail or operate falsely.

## 2.2 Problems on Electrical Transmission and Distribution System

The transmission and distribution grids are designed to carry fundamental 60 Hz frequency. Problem exists with higher frequencies (harmonics). Higher frequency currents do not fully penetrate the conductor and travel on the outer edge of the conductor. Such phenomenon is known as skin effect. This skin effect causes the decrease in the effective cross sectional area with the increase of resistance and losses which eventually heats up the conductors and anything connected to them. This heating effect results in tripping of the circuit breakers, heating of the phase and neutral conductor and premature failure of motors and transformers.

Harmonic gets more complicated in three phase applications. The triplen (odd multiple of three) harmonics (3rd, 9th, 15th,….etc.) are the major cause of the heat because they add together in the neutral conductor. The magnitude of the harmonic current produced by the triplens can approach twice the phase current. This causes the neutral conductor to overheat. Combination of positive and negative sequenced harmonics is the cause of abnormal amounts of heat in motors. The positive sequenced harmonics are the fundamental, 7th, 13th, 19th… etc. They tend to apply an additional forward force in the direction of the motor rotation.

The negative sequenced harmonics are the 5th, 11th….., etc. They present a force that opposes the motor rotation and tries to make motor rotate in the opposite direction. The force of these harmonics acting upon each other creates heat which leads to premature failure of motors. The circulating harmonics in the primary of the transformer create heat because of their higher frequencies.

In addition harmonic can cause:

1. Very high load current (up to the sum of all three phases) in the neutral of 3-phase system causing overheating of wires. Since only the phase wires are protected by circuit breakers of fuses, this can result in a potential fire hazard.
2. Overheating of standard electrical supply transformer which shortens the life of a transformer and will eventually destroy it. The cost of repair far exceeds the replacement cost of transformer it self.
3. High voltage and current distortion, excessive current draw on branch circuits and high neutral-to-ground voltage (Exceeding IEEE 1100-1992 "Recommended Practice for Powering and Grounding Sensitive Electronic Equipment" and manufacturer's specifications).
4. Poor power factor (>0.85 lagging) condition resulting in monthly utility penalty fees for major users.
5. Resonance that produces over-current surges.
6. False tripping of branch circuit breakers.

Other problems include:

- Production of unwanted "noise" on communications and data lines by electromagnetic or electrostatic coupling.
- Excessive heating of rotating machinery limiting the amount of converter load that can be carried.
- "Noise" on regulating and control system producing erroneous operations.
- Faulty metering and instrumentation readings, especially in induction disk devices such as watthour and overcurrent relays.
- Torque pulsations on ac motors.
- Excessive heating and failure of fluorescent and mercury lighting ballasts.

## 2.3 Telephone Interference

Harmonic currents flowing on the utility distribution system or within an end-user facility can create interference in communication circuits. Voltages induced in parallel conductors by the common harmonic currents often fall within the bandwidth of normal voice communications. Harmonics between 540Hz (9th harmonic) and 1200 Hz (20th harmonic) are particularly disruptive. The induced voltage per ampere of current increases with frequency. Triplen harmonics (3rd, 9th, 15th) are especially troublesome in four-wire systems. They are in phase in all conductors of a three-phase circuit and, therefore, add directly in the neutral circuit, which has the greatest exposure with the communications circuit.

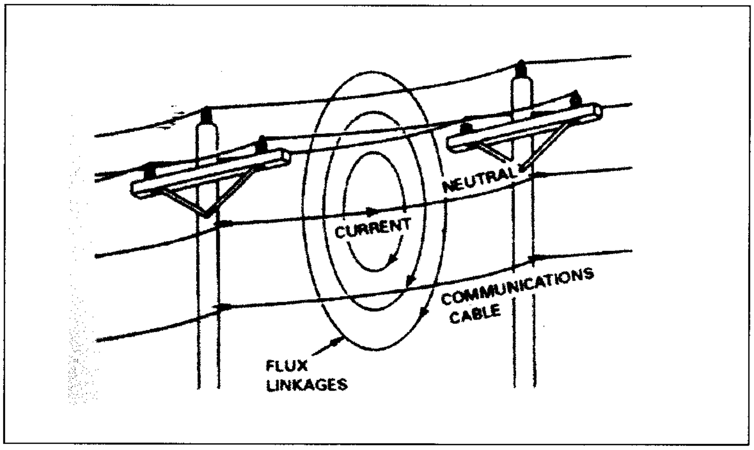


Figure 2.1. Telephone interference phenomenon.

Telephone noise originating from harmonic currents and voltages in power system is generally quantified as a telephone influence factor (TIF). The system recognizes that the noise induced by harmonic voltages or currents has a subjective effect on the telephone user since human ear is more susceptible to some frequencies than others.

TIF is a dimensionless value used to describe the interference of a power transmission line. Telephone influence factor is given by

$$\mathrm{TIF} = 1/U\ [(\textstyle\sum^{\infty}_{n=1} (K_f\, p_f\, U_f)^2]^{1/2} \text{ ......................................(B.1)}$$

where, n is an integer and n = 1,2,3…∞. U is the r.m.s voltage of the transmission line, $U_f$ is the harmonic voltage of frequency f, $K_f$ is the coupling coefficient, and $p_f$ is the weight of harmonic of frequency f, the maximum being 1 for f = 1000Hz.

# Chapter III

# Resonance Phenomena

## 3.1 Introduction

Electrical circuits with capacitance (C) and inductance (L) can resonate at one or more natural frequencies given by

$$f_R = 1 / 2\pi (LC)^{1/2} \qquad \text{.........................................(3.1)}$$

The capacitance and inductance exists by virtue of the physical construction of the conductive and nonconductive materials in the wires, connectors and other basic hardware. Resonance represents an interaction between components and occurs between components situated in parallel or in series with each other.

The resonance phenomenon can be compared to mechanical resonance in which mass is connected by spring to reference point. When displaced, the mass will oscillate back and forth until dampening effects bring the mass to a stop. The mass, spring and dampener are the mechanical equivalent of capacitance, inductance and resistance respectively. The tension of the spring is equivalent to the voltage. The natural frequency of a mechanical system is defined by an equation similar to that for an electrical system.

A resonance needs an exciting force. The mass must be pushed or displaced in the mechanical system. Similarly, the voltage must be pushed or displaced from its normal level in the electrical system. The severity of the resonance depends on the closeness of the match between the frequency of the exciting force and the strength of the dampening effects. Nonlinear loads such as adjustable speed drives produce a wide spectrum of harmonics from the 2nd order through the 50th order. A harmonic represents a displacement from the normal voltage level. There is great a potential that one of the harmonics will be tuned to the natural frequency and act as the exciting force for a system resonance. It is also possible for a system to be tuned to fundamental itself (60 Hz) giving rise to certain problems. Many electrical systems encounter resonance due to the installation, and then interaction of independent, but inter-related electrical components. Resonance leads to equipment failure, shortened lifetime and other costs. Resonance problems are becoming much more frequent due to the massive installation of semiconductor products (nonlinear loads), such as variable frequency drives, UPSs, welders and battery chargers.

Resonance is a form of system instability. Components of the overall system interact with each other to cause results that are not intended. Interaction usually involves passive components, such as inductors and capacitors, or control systems with crude control algorithms. Resonance involving passive components is relatively common when systems are modified. The addition of capacitors to improve power factor or the addition of a bus-applied passive harmonic filter may spawn resonance. There is also a potential for resonance when the supplying utility adds or changes capacitors or transformers near the customer's facility.

Resonance causes voltage or current to exceed design limits for system components. For example, capacitors will experience excessive voltage and will be charged and discharged with excessive currents. This leads to capacitor failure through voltage breakdown and heating. Depending upon the magnitude of resonance, failures can occur immediately or over many months. Sometimes system operators cannot correlate failures to their real cause due to the time lag until failure. The probability of system resonance is increased dramatically in the presence of semiconductor (nonlinear) loads which produce harmonics that excite the natural frequencies inherent in the electrical system. A variable frequency drive produces harmonics at many frequencies, including, for example, the 29th order. The addition of the drive (which contains capacitors) or a bank of power factor capacitors might create a 29th order natural frequency.

Resonance elimination prevents component failures caused by heating and voltage breakdown. Resonance elimination results in good power factor, higher efficiency and safe operation of equipments. It is not uncommon to find electrical systems in industrial applications where power factor correction capacitors and tuned filters have been disconnected on account of overheating or frequent failure, all caused by resonance.

## 3.2 Parallel Resonance

All circuits containing both capacitances and inductances have one or more natural frequencies. When one of these frequencies lines up with a frequency that is being produced on the power system, resonance can develop in which the voltages and currents at that frequency continue to persist at very high values. This is the root of most problems with harmonic distortion on power system.

Parallel resonance occurs when a capacitor is connected to the same busbar as the harmonic source. Parallel resonance can occur between the source and the capacitor.

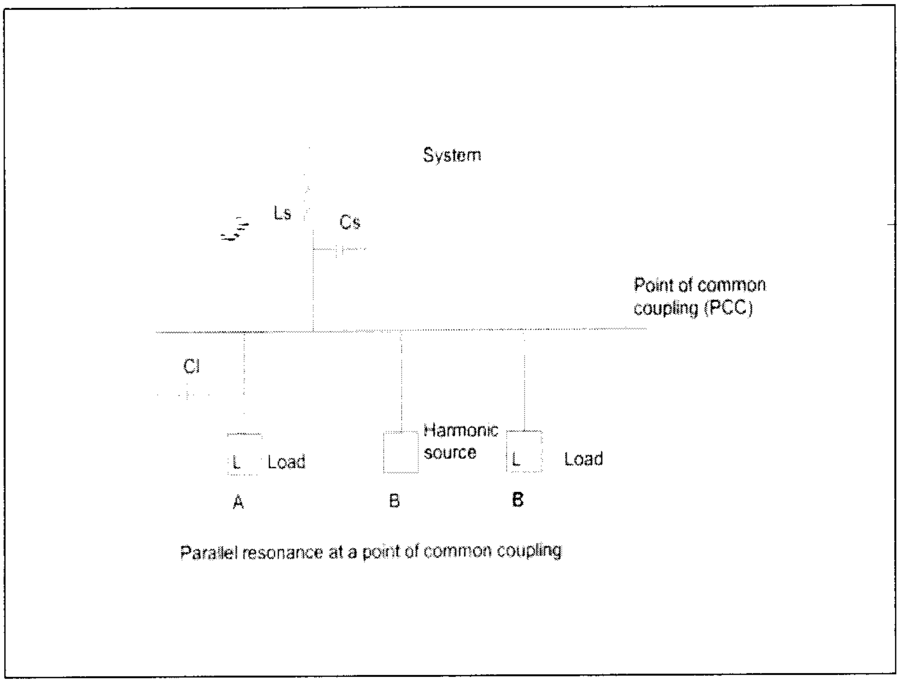


Figure 3.1. Parallel resonance at a point of common coupling.

If we assume the source to be entirely inductive then the resonant frequency can be given by

$$f_p = f\ (S_S / S_C)^{1/2} \text{ ................................................ } (3.2)$$

where, f = fundamental frequency in Hz.,

$f_p$ = parallel resonant frequency in Hz.,

$S_S$ = source short circuit rating in Var.,

$S_C$ = capacitor rating Var.

In figure 3.1, the harmonic current from the consumer B encounters high harmonic impedance at the busbar may be because of a resonance between the system inductance Ls and either the system capacitance Cs or the load capacitance $C_l$. In order to determine which resonance condition exists it is necessary to measure the harmonic currents in consumer load, supply and harmonic voltage at supply. Generally, if the current flowing into the power system from the bubsar is small while the harmonic voltage is high, resonance within the power system is indicated. If instead a large harmonic current flows in consumer A's load and leads the harmonic voltage at busbar, resonance between the system inductance and load capacitor is indicated.

## 3.3 Series Resonance

The load can be ignored at the higher frequencies because of the reduction in capacitive impedance and under this condition there will be series resonance condition when

$$f_s = f\ \{(S_t / S_C Z_t) - (S_l^2 - Sc^2)\}^{1/2} \qquad (3.3)$$

where,

$f_s$ = the series resonant frequency (Hz),

$S_t$ = the transformer rating,

$Z_t$ = is the transformer per unit impedance ,

$S_l$ = the load rating (resistive).

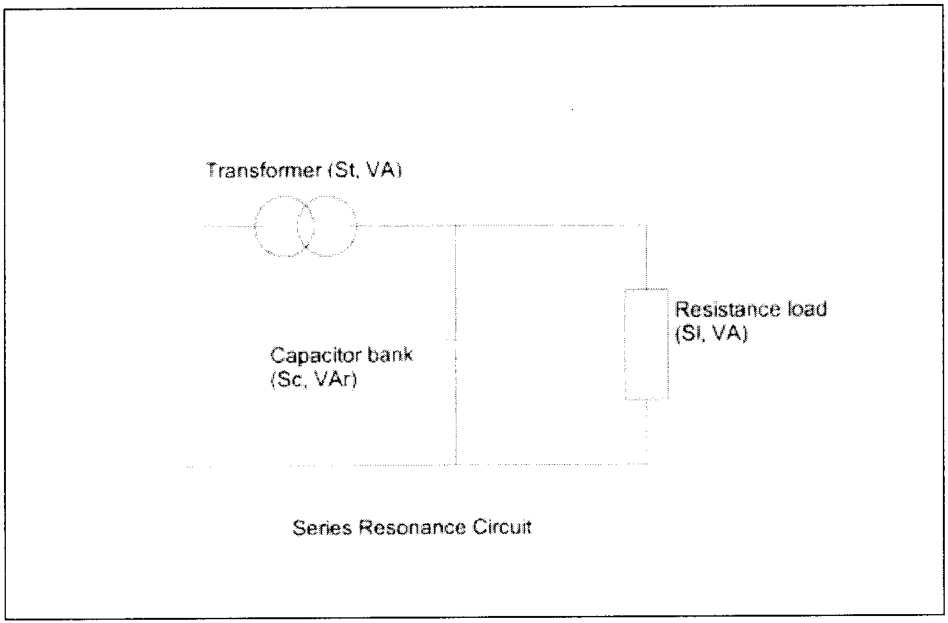


Figure 3.2. Series resonance circuit.

In case of the series resonance, high capacitor current can flow for relatively small harmonic voltages. The Quality Factor (Q) determines the actual amount of current that will flow in the circuit.

The damping provided by the resistance in the system is often sufficient to prevent voltage and current distortions. As little as 10 percent resistive loading can have beneficial impact on peak impedance. Similarly, if there is a significant length of lines or cables between the capacitor bus and the nearest transformer, the resonance will be suppressed. Lines and cables can add a significant amount of the resistance to equivalent circuit. The worst resonant conditions occur when capacitors are installed on substations buses where transformer dominates the system impedance and has high X/R ratio. The relative resistance is low and corresponding parallel resonant impedance peak is very sharp and high which is the common cause of capacitor failure or the failure of the load equipment.

Motor loads are primarily inductive and provide little damping. They may increase distortion by shifting the system resonant frequency closer to a significant harmonic. Small fractional-horsepower motors may contribute significantly to damping because their apparent X/R ratio is lower than large three-phase motors.

# Chapter IV

# Harmonic Filters and Harmonic Filter Design

## 4.1 Harmonic filters

Filter circuits which are specially designed for the purpose of eliminating harmonic current or voltage distortions are called harmonic filters.

There are two types of filters used for filtering the harmonic distortions:

1. Passive filters
2. Active filters

### 4.1.1 Passive Filters

The main components of a passive filter are inductance, capacitance and resistance. They are relatively cheaper than other methods of harmonic elimination. Passive filters are applied either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to create a resonance at a selected harmonic frequency.

The common passive filter configurations are:

- Single tuned
- 1st order high-pass
- 2nd order high-pass
- 3rd order high-pass

The most common type of passive filter is single-tuned notch filter which is the most economical and frequently sufficient for the application. An example of 480-volt filter arrangement is shown in Figure 4.1.

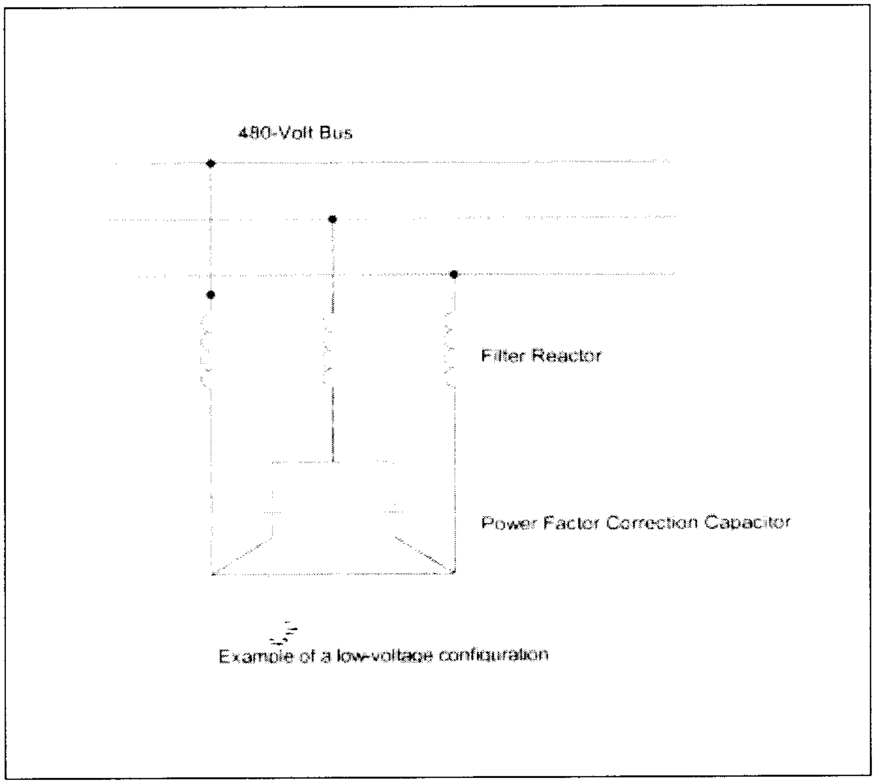


Figure 4.1. Low-voltage filter configuration.

The filter is single-tuned to present low impedance to a particular harmonic current. It is connected in shunt with the power system there by diverting the harmonic currents from their normal flow path on the line into the filter. Notch filter can provide power factor correction in addition to harmonic suppression.

As shown in Figure 4.1, a common-delta connected low-voltage capacitor bank converted into a filter by adding an inductance in series. Then the relation between notch harmonic $h_{notch}$ and fundamental frequency is given by

$$h_{notch} = (X_C / 3X_f)^{1/2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

where, $X_C$ is the reactance of one leg of delta rather than the equivalent line-to-neutral capacitive reactance.

One small disadvantage of adding a filter is that it creates a sharp parallel resonance point at the frequency below the notch frequency. This resonant frequency must be safely away from any significant harmonic. The filters are commonly tuned slightly lower than the harmonic to be filtered to provide a margin of safety in case there are some changes in system parameters. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance higher into the harmonic. This could present a situation worse than without a filter because the resonance is generally very sharp. This is the reason for adding the filters to the system starting with the lowest problem harmonic. For instance, installing a seventh harmonic filter usually requires that a fifth-harmonic filter also be installed. The new parallel resonance with a seventh harmonic filter only would have been very near the fifth, which is generally disastrous.

The filter configuration shown in the Figure 4.1 does not admit zero-sequence currents because the capacitor is connected in delta. This makes it largely ineffective for filtering triplen harmonics. Passive filters should always be placed on a bus where $X_{SC}$ can be expected to remain constant. While the notch frequency will remain fixed, the parallel resonance will move with system impedance.

The configuration of single tuned (low-pass) shunt filter is shown in Figure 4.2.

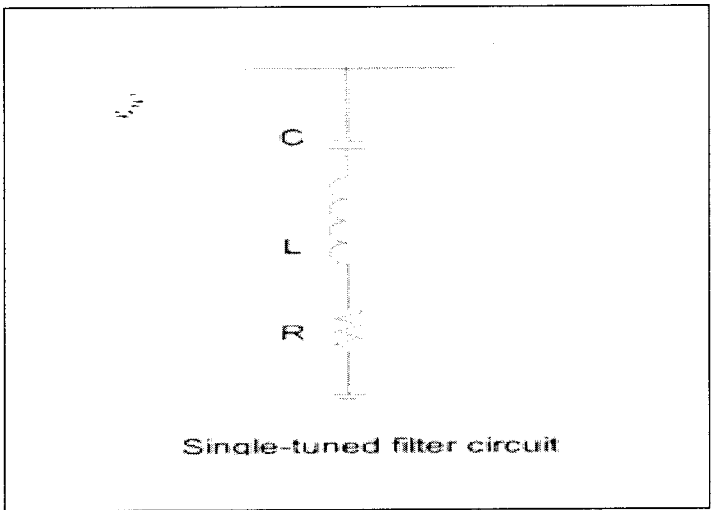


Figure 4.2. Single-tuned filter circuit.

In the single-tuned filter circuit, a capacitor, an inductor and a resistor are connected in series. This filter is also known as low pass filter.

The first order high-pass filter is not normally used, as it requires a large capacitor and has excessive loss at fundamental frequency.

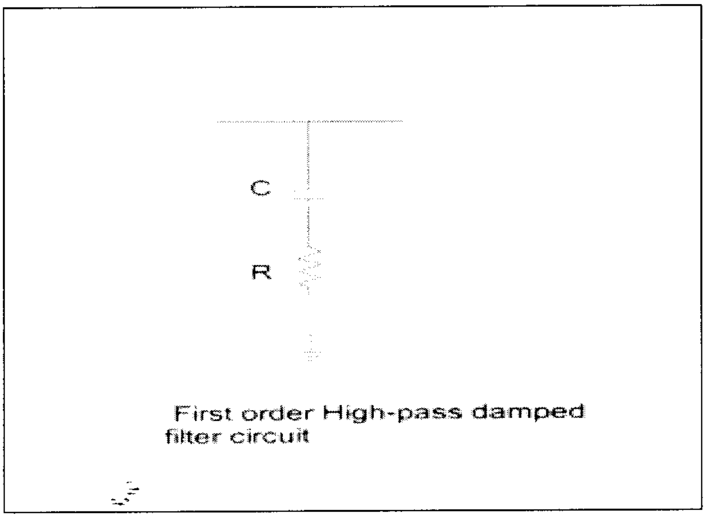


Figure 4.3. First order high-pass damped filter circuit.

The second order high-pass filter provides the best filtering performance, but has higher fundamental frequency losses as compared with the third order.

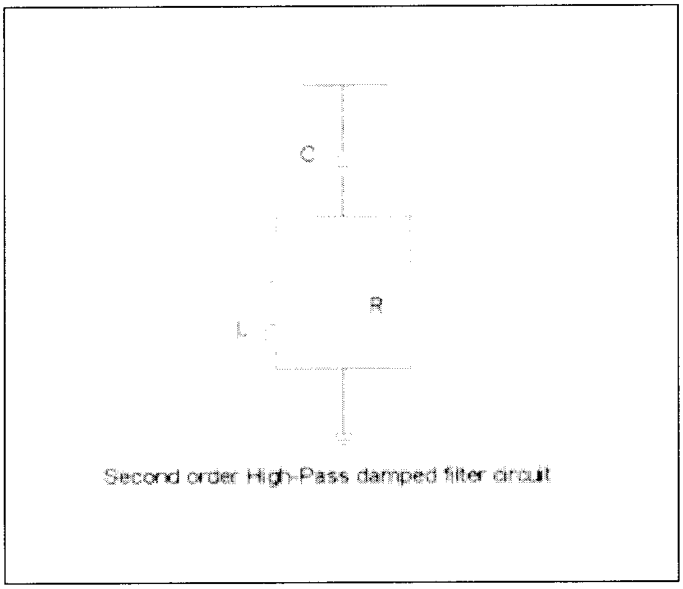


Figure 4.4. Second order high-pass damped filter circuit.

The third order high-pass filter's main advantage over second order is a substantial reduction in fundamental frequency loss, owing to increased impedance at that frequency caused by the presence of the capacitor $C_2$. Moreover, the rating of $C_2$ is very small compared with $C_1$.

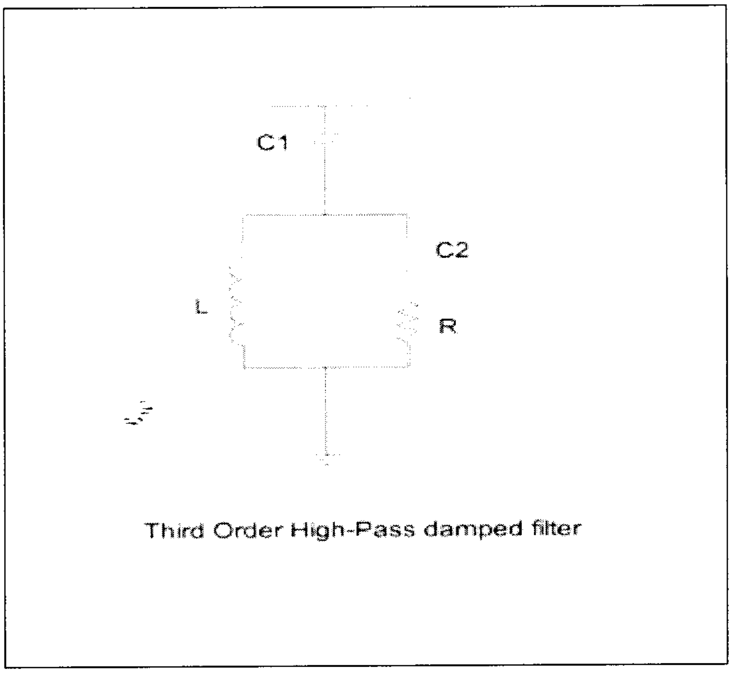


Figure 4.5. Third order high-pass damped filter circuit.

The filtering performance of the C-type high-pass filter lies between those of second and third. Its main advantage is a considerable reduction in the fundamental frequency loss since $C_2$ and L are series tuned at that frequency. This filter is more susceptible to a fundamental frequency deviations and component value drifts.

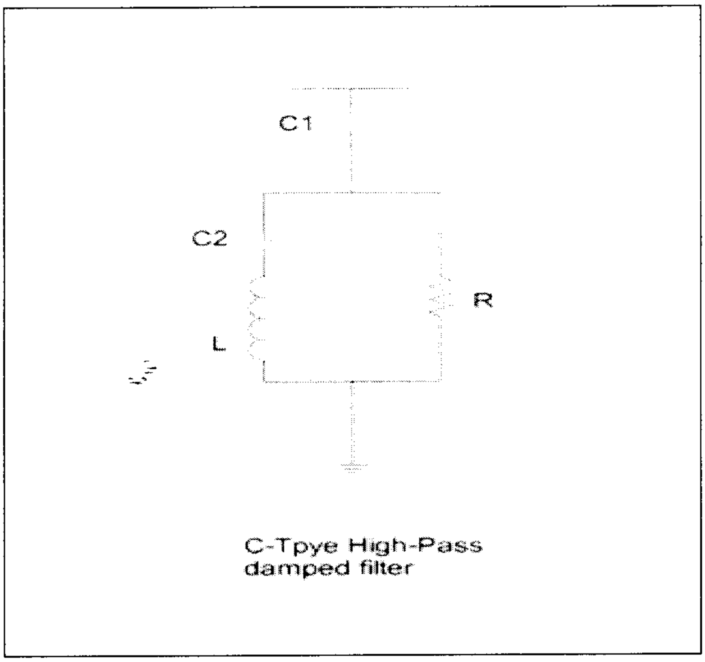


Figure 4.6. C-type high-pass damped filter circuit.

Advantages of damped high pass filters:

1) Its performance and loading is less sensitive to temperature variation, frequency deviation, component manufacturing tolerances, loss of capacitor elements, etc.
2) Provides low impedance for a wide spectrum of harmonics without the need for subdivision of parallel branches with increased switching and maintenance problems.
3) The use of tuned filters often results in parallel resonance between the filter and system admittances at a harmonic order below the lower tuned filter frequency, or in between tuned filter frequencies. In such cases the use of one or more damped filters is a more acceptable alternatives.

Disadvantages:

1. To achieve a similar level of filtering performance the damped filter needs to be designed for higher fundamental VA ratings, though in most cases a good performance can be met within the limits required for power factor correction.
2. The losses in the resistor and reactor are generally higher.

### 4.1.2 Active Filters

Active filters are relatively new types of devices for eliminating harmonics. They are based on sophisticated power electronics and much more expensive than passive filters.

However, they have distinct advantage that they do not resonate with the system. They can be used in very difficult circumstances where passive filters cannot operate successfully because of where the parallel resonance lies. They can also address more than one harmonic at a time and combat other power quality problems such as flicker. They are particularly useful for large, distorting loads from relatively weak points on the power system.

## 4.2 Harmonic Filter Design

Size of a filter is defined as the reactive power that the filter supplies at fundamental frequency. This reactive power is equal to the fundamental reactive power supplied by capacitors.

The design of filters involves the following steps.

- The harmonic current spectrum produced by the non-linear load is injected into a circuit consisting of filters in parallel with the a.c. system (as shown in fig 4.7.) at the relevant frequencies and the harmonic voltages are calculated.
- The calculated harmonic voltages are used to determine the specified parameters, i.e. voltage distortion D, TIF and IT factors.
- The stresses in the filter components namely capacitors, inductors and resistors are calculated. With the result, their ratings and losses are determined. Current source, filter admittance and system admittance require detail consideration in filter design.

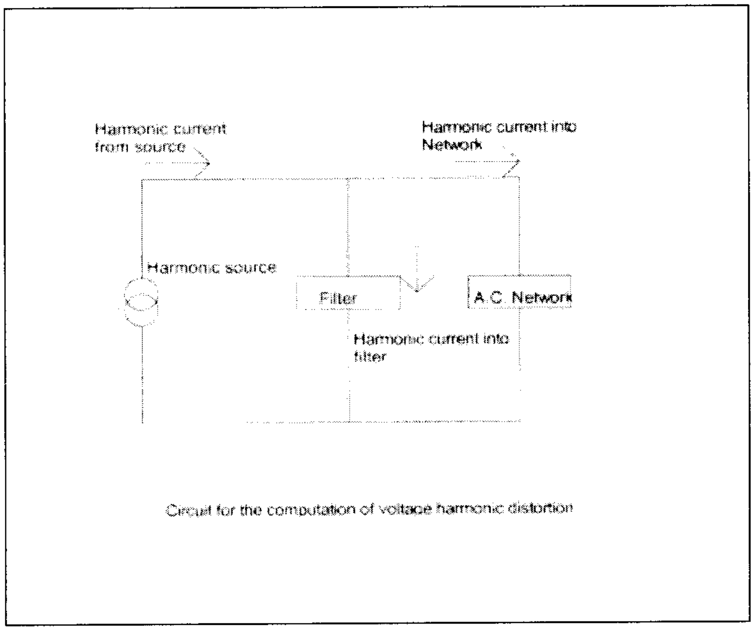


Figure 4.7. Circuit for the computation of voltage harmonic distortion.

### 4.2.1 Quality Factor (Q)

Q-factor is an important property of capacitors and inductors.

Tuning characteristics of a filter is described by its quality factor (Q). Q is a measure of sharpness of tuning. For series filter resistance, Q is given by

$$Q = n\, X_L / R \ldots\ldots\ldots\ldots (4.2)$$

where,

$R$ = series resistance of filter elements,

$n$ = tuning harmonic, and

$X_L$ = reactance of filter reactor at fundamental frequency.

The value of R consists of only the resistance of the inductor which often results in a very high value of Q and a very sharp filtering action. This design results in a filter that is very economical to operate and has a satisfactory typical single-filter application.

A resistor is added in parallel with the reactor to create a high-pass filter. In this case, Q is given by the inverse of the above equation. High-pass filters are usually used only at the 11th and 13th harmonics, and higher. It is not economical to operate such filter at the 5th and 7th harmonics because of the amount of losses and the size of the resistor.

The high Q filter is sharply tuned to one of the lower harmonic frequencies and a typical value is between 30 and 60. The low Q filter, typically in the region of 0.5 to 5 has low impedance over a wide range of frequencies. When used to eliminate the higher order harmonics for instance 17th and up, it is also known as a high pass filter.

### 4.2.2 Harmonic Filter Design Example:

Design of a harmonic filter considering a 3-phase 480-volt bus is illustrated through a simple example. A single-tuned 480-volt notch filter as shown in Figure 4.1 is designed for the fifth harmonic and it is tuned just below the harmonic frequency of concern. This method allows for tolerances in the filter components and prevents the filter from acting as a direct short circuit for the offending harmonic current.

As mentioned earlier the following are the general methods for applying filters:

- A single-tuned shunt filter is applied and designed for the lowest generated frequency.
- Voltage distortion levels are determined.
- Filter elements are varied according to the specified tolerances and filter's effectiveness is checked.
- Frequency response characteristic is checked to verify that the newly created parallel resonance is not close to a harmonic frequency.

The actual kvar of the capacitor is found using

$$\text{kvar}_{\text{actual}} = \text{kvar}_{\text{rated}} (\text{kV}_{\text{actual}} / \text{kV}_{\text{rated}})^2 \quad \text{.......................(4.3)}$$

In this problem, the rated and actual voltages are same, so the actual kvar of the capacitor is the rated kvar, 500 kvar. The fundamental frequency current for the capacitor bank is

$$I_{\text{Flcap}} = \text{kvar}_{\text{actual}} / (\sqrt{3})\ \text{kV}_{\text{actual}}$$

$$= 500 / (\sqrt{3}) * 0.480 = 601.4\ \text{A.} \quad \text{.....................(4.4)}$$

The equivalent single-phase impedance of the capacitor bank is

$$X_{CY} = \text{kV}^2_{\text{rated}} / \text{Mvar}_{\text{rated}}$$

$$= (0.480)^2 / 0.5 = 0.4608\ \Omega \text{......................(4.5)}$$

The filter reactor impedance is determined using

$$X_R = X_C / n^2 = 0.4608 / (4.7)^2 = 0.02086\ \Omega \text{..............(4.6)}$$

Including the filter reactor increases the fundamental current to

$$I_{F1filter} = V_{bus} /(\sqrt{3})(X_C + X_R)$$

$$= 0.480 /(\sqrt{3}) (-0.4608 + 0.0209) = 629.9 \text{ A}......(4.7)$$

Since the filter draws more fundamental current than the capacitor alone, the supplied kvar compensation is larger than the capacitor rating and can be determined using

$$kvar_{actual} = (\sqrt{3}) * V_{bus} * I_{F1filter}$$

$$= (\sqrt{3}) *480*629.9 = 524 \text{ kvar}................(4.8)$$

Capacitor ratings should be compared with the standard capacitor limits. Filter reactor specifications should include both the fundamental and harmonic current value. The harmonic current should be determined assuming a reasonable value for background distortion from the other sources. In this design, it was assumed that the utility side voltage distortion was 1.0 percent.

The quality factor Q is determined using

$Q = n X_L / R$,

where,

R = series resistance of filter elements,

n = tuning harmonic,

$X_L$ = reactance of filter reactor at fundamental frequency.

The reactors used for larger filter applications are generally built with an air core, which provides linear characteristics with respect to frequency and current. Reactors for smaller filters are built with a steel core. The fundamental X/R ratio is usually between 50 and 150. A series resistor may be used to lower this ratio, if desired, to produce a filter with more damping. The reactor should be rated to withstand a short circuit between reactor and capacitor.

Table 1. Harmonic Filter Design Example:

## Low Voltage Filter Calculation

System Information:

| | | | |
|---|---|---|---|
| Filter specification: | 5th | | |
| Capacitor Bank Rating | 500 kvar | Rated Bank Current | 601 Amps |
| Nominal Bus Voltage | 480 Volts | Capacitor Current (actual) | 601.4 Amps |
| Filter Tuning Harmonic | 4.7th | Capacitor Impedance (wye equivalent) | 0.4608 W |
| Reactor impedance | 0.0209 W | Full load current (actual) | 629.9 Amps |
| Full load current (rated) | 629.9 Amps | Transformer Nameplate | 1500 kVA, 6 % |
| Load harmonic current | 30 % Fundamental | Utility harmonic current | 47.7 Amps |
| Power system frequency | 60 Hz | Capacitor Rating | 480 Volts, 60 Hz |
| Derated Capacitor | 500 kvar | Filter Tuning Frequency | 282 Hz |
| Capacitor value (wye equivalent) | 5756.5 µF | Reactor rating | 0.0553 m H |
| Supplied compensation | 524 kvar | Utility harmonic voltage source | 1% THD |
| Load harmonic current | 180.4 Amps | Max. Total Harmonic Current | 228.1 Amp |

## Capacitor duty calculations:

| | | | |
|---|---|---|---|
| Filter RMS Current | 669.9 Amps | Harmonic Capacitor Voltage | 36.4 Volts |
| RMS Capacitor Voltage | 504.1 Volts | Fundamental capacitor Voltage | 502.8 Volts |
| Maximum Peak Voltage | 858.0 Volts | | |

## Capacitor Limits: (IEEE Std. 18-1980)

| | Limit | Actual |
|---|---|---|
| Peak Voltage | 120% | 112% |
| Current | 180% | 111% |
| KVAR | 135% | 117% |
| RMS Value | 110% | 105% |

## Filter Reactor Specifications

| | | | |
|---|---|---|---|
| Reactor Impedance | 0.0209 W | Fundamental Current | 629.9 Amps |
| Reactor Rating | 0.0553 m H | Harmonic Current | 228.1 Amps |

# Chapter V

# Benefits of Harmonic Filters

## 5.1 Economic Benefits and Cost Effectiveness

Power quality problems can adversely affect company's economy. According to the studies conducted by the Canadian Electrical Association, power quality problems such as harmonics, voltage sags and surges, and transients are estimated to cost about $1.2 billion annually.

The financial impacts of power disturbances vary by industry. The US based Electric Power Research Industry found that a mere two seconds of power disruption in the paper industry results in production losses of about $30,000 per event. Similarly, momentarily power disturbances in the chemical industry can cost large companies up to $75 million per year.

Power quality problems are common in various industries in their facilities. Some of the industries suffering from these problems and methods used to overcome those difficulties are described below.

### 5.1.1 Telecommunications

Most of the telecommunications companies suffer from the problems with failing capacitors and telephone interference (from power lines). The installation of a fixed harmonic filter bank, which provides the necessary power factor correction while eliminating capacitor failures, is the most cost-effective solution.

### 5.1.2 Manufacturing

Different manufacturing companies are experiencing power quality problems. A plastic manufacturing company experiencing difficulties correcting the facility's electrical power factor to greater than 90% by the addition of more capacitors only served to accelerate their failure rate. In some cases, the capacitor lasted only few months. After a survey, experts recommended a fixed filter bank on each of the facility's two main electrical services. The fully engineered harmonic filter installation provided the company with the required power factor correction to eliminate the surcharges. The filter configuration is immune to power quality disturbances ensuring a long life expectancy for the equipment.

### 5.1.3 Transportation

A company in a transportation industry was experiencing premature failure of capacitors in its existing harmonic filter bank. After conducting a power quality study of the facility it was found that the filter was actually amplifying harmonic distortion. Using computer models of the electrical system, acceptable operating modes and necessary upgrades were identified for the filter bank to achieve reliable operation. The company received power quality solutions report outlining the filter operating modes, which would produce excessive harmonic distortion in the electrical system, potentially causing violent failure of the filter bank and/or over-heating of motors and other electrical equipment. It was recommended that the company should operate the filter with a new optimal configuration and be refurbished with capacitors designed to withstand the stress of the harmonic filter application.

## 5.2 Effects of Harmonic Filter Bank Tuning (Tuned and Detuned Banks) on the Economic Design of Harmonic Filters

When designing or applying a harmonic filter, the main consideration is the tuning of the filters to the specific harmonic or frequency. The decisions should be made considering the purpose of filters. As mentioned in the previous chapters, harmonic filters are generally installed to achieve one or more of the following objectives:

1. Capacitors are required to improve power factor, and possible system interaction may occur with the installation of a plain capacitor bank.

2. Permissible distortion limits of the local utility or IEEE-519 are exceeded, and filters are required to reduce them.

Frequency scan for a 4.2nd, 4.8th, and 5th harmonic filter gives the information about the apparent impedance as a function of frequency. Frequency scan shows how the tuning point affects the apparent impedance, mainly in the area of tuning (near 5th harmonic).

The impedance scan is useful as it gives an indication of the filter characteristics. For example, the filter tuning point can be determined by looking at the minimum impedance, or "notch". In addition, the anti-resonant point, the peak just below the tuning point, can also be determined. The anti-resonant point always exists below the tuned frequency of a filter, and significant harmonics at this frequency should be avoided. When applying de-tuned filters below the 4.2nd, careful consideration should be given to possible resonant concerns at the 3rd harmonic.

Whether to tune, de-tune or partially de-tune is a question of economy, objective of filtering, and negative system interaction. A tuned filter costs more than a partially de-tuned filter, and likewise a partially de-tuned filter costs more than a de-tuned filter.

Filter currents for various tuning points for a system are illustrated in Table 2. The Table is based on 100 amps of 5th harmonic current injected from the non-linear load. This current may flow back to the utility or into the harmonic filter, and is dependent upon the filter impedance and the system impedance at the 5th harmonic. Table 2 shows that the 5th harmonic filter will absorb most of the harmonic current and very little will be absorbed by the utility. As a result, the fifth harmonic filter would require a current rating of 99 Amps. The 4.8th harmonic filter absorbs less, and would require a current rating of 70 Amps. The 4.2nd harmonic filter absorbs very little harmonic current (20 Amps), while the utility and the remaining system absorbs the remaining 80 Amps. Tuning the filter closer to the fifth harmonics requires higher reactor current ratings, (and also capacitor voltage ratings) which result in higher cost.

Table 2. Filter Performance

| Filter Type | Filter Current (amps) | Utility System (amps) |
|---|---|---|
| 5th | 99 | 1 |
| 4.8th | 70 | 30 |
| 4.2nd | 20 | 80 |

The choice of tuning frequency is based on the objective of the harmonic filter and economics.

### 5.2.1 De-Tuned Filters (Tuning Between 4.0 and 4.4)

De-tuned filter bank is the best choice for the purpose of power factor correction. This filter will do little for removing any harmonic distortion present in the system but will allow the installation of a large capacitor bank without any adverse system interactions. De-tuned filter banks are less costly and are more reliable than partially de-tuned and tuned filter banks. The anti-resonant frequency should be considered to assure that it does not fall near the 3rd harmonic.

### 5.2.2 Partially Tuned Filters (Tuning Between 4.4 and 4.8)

In some situations, a filter (or capacitor bank) is required to improve power factor, and at the same time distortion limits are exceeded. In this situation, a de-tuned filter bank is usually the best choice. A de-tuned bank offers less risk and is typically less costly than a tuned filter bank.

### 5.2.3 Tuned Filters (Tuning Between 4.8 and 5.0)

A tuned filter bank is used for the purpose of reducing the harmonic distortion to acceptable limits. A tuned filter bank will require the least amount of kvar to bring the distortion down within limits, but will require the highest level of engineering design. It has the highest level of risk, since it draws most of the harmonics present in the industrial system. The application of this type of filter should include a detailed harmonic analysis by the manufacturer.

### 5.2.4 Other Filter Types

Fifth, seventh, and eleventh order filter banks are designed with optimization and specific current distortion limits in mind. They are costly than simple tuned filter banks but are much more effective in reducing the system distortion. They are generally applied to the systems with large amounts of non-linear loads.

## 5.3 Other Benefits of Harmonic Filters

Correctly applied in the three phase four wire electrical power system, the harmonic filter provide the following benefits:

- Shunts harmonic currents.
- Reduces neutral current.
- Safeguards neutral conductors.
- Improves system protection.
- Reduces local neutral to ground voltage.
- Reduces peak phase current.
- Reduces average phase current.
- Reduces transformer overload.
- Increases system capacity.
- Reduces system losses.
- Reduces total harmonic distortion.
- Improves power factor on non-linear loads.
- Improves phase current balance.
- Improves phase voltage balance.
- Carry through single phase outage.
- Cost effective solution.

## 5.4 Comparison Among Various Methods of Harmonic Elimination

There are various methods for the elimination of harmonic distortions. All of them have advantages and disadvantages in terms of design, application and economy. Some of the most popular techniques are:

- 6-pulse AC drive without a DC link choke: The simplest design of AC drives. Does not provide any harmonic mitigation capability.
- 6-pulse AC drive with a DC link choke: The choke provides reduction of low frequency harmonics produced by the drive.
- Input line reactor: Reduces surges or spikes on the line. Provides enough harmonic mitigation on distribution systems that have a very small percentage of non-linear loading.
- 12-pulse converter with auto transformer: Reasonable performance and cost effective, but does not guarantee meeting IEEE 519-1992 limits without analysis. Less component count and design complexity compared to 18-pulse. An auto transformer will have a lower cost and smaller physical size (easier to mount in the enclosure line-up) than an isolation transformer.
- 12-pulse converter with isolation transformer: Reasonable performance and cost effective, but does not guarantee meeting IEEE 519-1992 limits without analysis. Less component count and design complexity compared to 18-pulse. An isolation transformer supplies slightly less THD than an auto transformer and non-proprietary designs are more readily available.
- 18-pulse converter with auto transformer: Can guarantee meeting IEEE 519-1992 limits at the drive input terminals without analysis provided the input power phases are balanced within 1 percent. An auto transformer will have a lower cost and smaller physical size (easier to mount in the enclosure line-up) than an isolation transformer.
- 18-pulse converter with isolation transformer: Can guarantee meeting IEEE 519-1992 limits at the drive input terminals without analysis provided the input power phases are balanced within 2 percent. An isolation transformer supplies less THD than an auto transformer and non-proprietary designs are more readily available.

### • Oversizing or Derating of the Installation

This solution does not attempt to eliminate the harmonic currents flowing in a low voltage (less than 1,000VAC) electrical distribution system but rather to "mask" the problem and avoid the consequences. When designing a new installation, the plan is to oversize all elements likely to transmit harmonic currents, namely transformers, cables, circuit breakers, engine generator sets and distribution switchboards. The most widely implemented solution is oversizing of the neutral conductor. In existing installation, the most common solution is to derate the electrical distribution equipment subjected to the harmonic currents. The consequence is an installation that cannot be used to its full potential. The result is a major increase in the cost of electrical distribution system.

- **Specially Connected Transformers**

This solution inhibits propagation of third-order harmonic currents and their multiples. It is a centralized solution for a set of single-phase loads. However, it produces no effect on other harmonic orders that are not multiples of three (5th, 7th, etc). On the contrary, this solution limits the available power from the source and increases the line impedance.

The consequence is an increase in the voltage distortion due to the other harmonic orders.

- **Series Reactors**

This solution is used for variable speed drives and three phase rectifiers. A reactor is not expensive, but has limited effectiveness. One must be installed for each non-linear load. Current distortion is divided by a factor of approximately two.

The consequence is an increase in the harmonic current.

- **Tuned Passive Filter**

Tuned passive filters trap harmonic currents in L/C circuits. A filter comprises a series of "stages", each corresponding to a harmonic order. 5th and 7th order harmonics are commonly filtered.

A filter may be installed for one load or a set of loads. Its design requires in-depth study of the AC system. Component sizing depends on the harmonic spectrum of the load and the impedance of the power source. Rating must be coordinated with reactive power requirements of the loads, and it is often difficult to design a filter to avoid leading power factor operation for some load conditions. This solution is effective and its design depends entirely on the given power source and the loads.

- **Active Harmonic Filters**

The idea of Active Harmonic Filters is relatively old. However, lack of effective techniques slowed its development for a number of years. At present, widespread use of IGBT components and availability of new digital signal processing (DSP) components are paving the way to a much brighter future for active harmonic filters. The active harmonic filter concept uses power electronics to introduce current components, which cancel the harmonic components of the non-linear loads.

- **Series Filters**

This type of filter is connected in series with an AC distribution network and compensates harmonic currents generated by the load. This solution is technically similar to line conditioners and must be sized for the total load rating.

- **Parallel Filters**

Parallel filters are also called shunt filters. These filters are connected in parallel with an AC line and need to be sized only for the harmonic current drawn by the non-linear load(s).

- **Hybrid Filters**

Hybrid filter combines an active filter and a passive filter. In certain cases, it may be a cost-effective solution. The passive filter carries out basic filtering (5th order, for example) and the active filter, through its precise and dynamic technique, covers the other harmonics.

# Chapter VI

# IEEE 30 Test Bus System

## 6.1 System Introduction and Harmonic Analysis

One line diagram of IEEE 30 Test Bus System is shown in Figure 6.1. The system contains 30 buses, transformers, synchronous motors, transmission lines and generators. For the purpose of harmonic analysis, four different kinds of harmonic sources are injected at the load locations by using the harmonic source library of the SKM Tools For Windows software.

The four different kinds of harmonic sources injected in the system are: a) Typical 6 pulse IGBT, b) ARC furnace, c) IEEE 6 pulse, and d) Typical 12 Pulse. Harmonics of the orders ranging from 2nd to 31st are present in the system at different locations. Arc Furnace causes the harmonics of orders 2nd to 10th. 3rd harmonic is the most dominant one.

When non-linear loads are present (more than 20% of the total load) and capacitor bank is added to compensate for the power factor as required for the linear loads, parallel resonance conditions could possibly be present. Harmonic analysis simulation is performed for the entire system and found that the large amounts of harmonic distortions (voltage and currents) are present in the system whose values are beyond the IEEE 519-1992 limits. The shunt passive filter is placed across the incoming line and is designed to offer very low impedance to the harmonic currents present in the non-linear load current spectrum. The shunt passive filter processes flow of electrical energy at fundamental frequency from the source but offers a lower impedance path for the flow of harmonic energy needed by the non-linear load. In other words, the harmonic component needed by the non-linear load is provided by the shunt filter rather than the ac source. The fundamental frequency energy component flowing into the shunt filter also provides leading VARs which can be used for power factor correction.

Low pass harmonic filters, referred to as broadband harmonic suppressors, offer a non-invasive approach to harmonic elimination. Rather than being tuned for specific harmonic, they filter all harmonic frequencies, including the third harmonic. Since they are connected in series with the non-linear load with a large series connected impedance, they don't create system resonance problems. No field tuning is required with the low pass filter. Low pass filter tuned to 5th harmonic is connected at bus 0025. The application of filter reduced the total harmonic distortion (THD) of voltage below 5% and total harmonic distortion of current (THID) below 15%. Remaining harmonics in the system were eliminated by using a low pass filter at bus 0027 and a high pass filter at bus 0028.

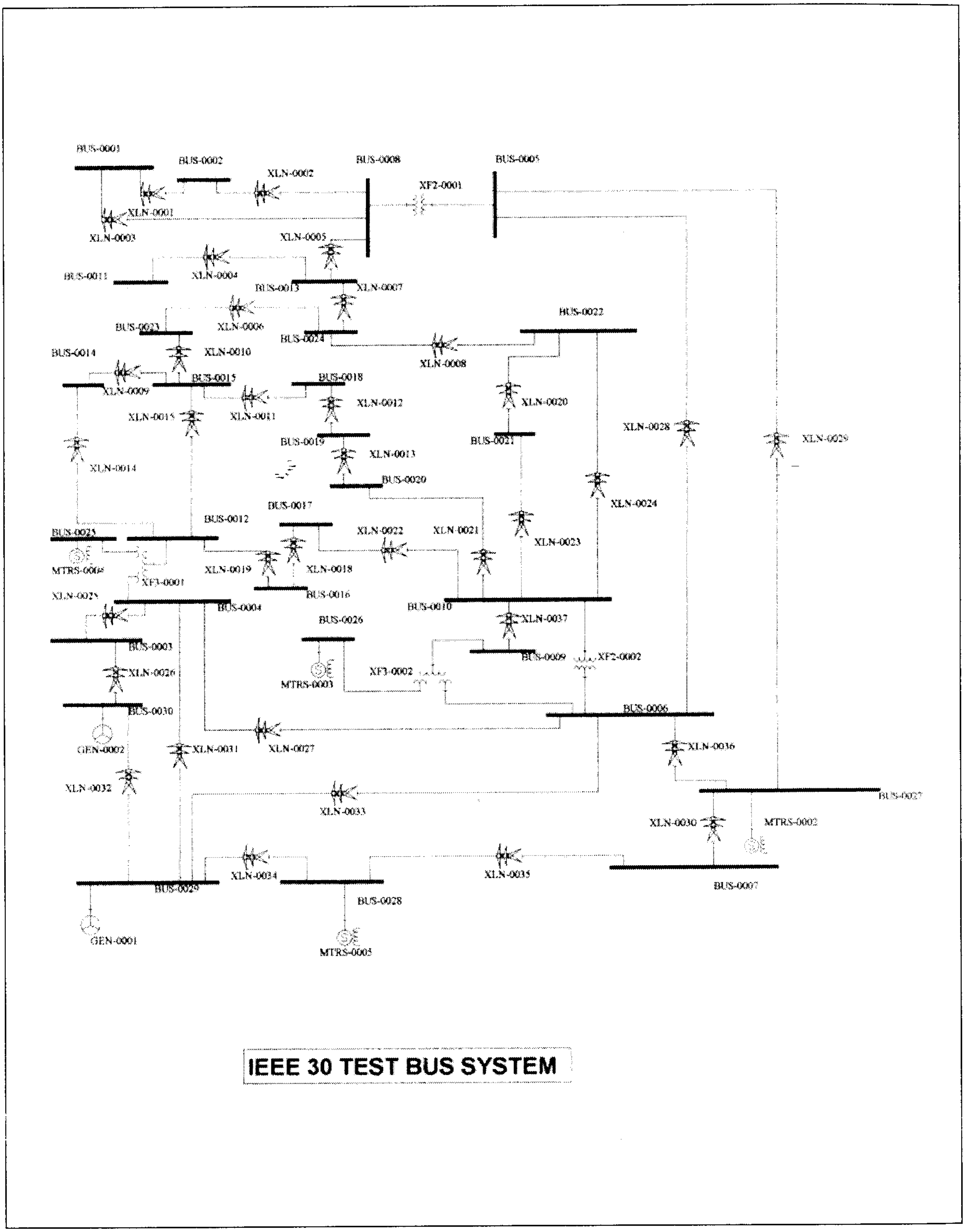


Figure 6.1. IEEE 30 Test Bus System

## 6.2 Conclusion and Future Recommendations

### 6.2.1 Conclusion

Based on information obtained from a computer study, disturbances present at various locations were determined. Harmonics of different orders and magnitudes caused a large amount of distortions. The distortions were beyond the limits set by IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (IEEE-519, 1992). For the elimination of harmonics, low pass and high pass filters were designed by using SKM Tools for Windows software. For the best overall result, filters were installed close to the non-linear loads. The application of filters reduced the distortions. Total harmonic distortions of voltage and current were reduced below the IEEE-519, 1992 limits (5% for voltage THD and 15% for current THD).

This harmonic elimination method is very cost effective, robust and applicable to industrial plants and facilities with non-linear system.

### 6.2.2 Future Recommendations

Future research should be focused on the following recommendations:

1. Analysis and design of passive filters avoiding bulky and voluminous components.
2. Active filtering using harmonic current injection for power factor correction.
3. Analysis and application of shunt active power filters which function as current sources and cancel the current harmonic and reactive components generated by the load.
4. Analysis toward active filtering applying high-speed, real time calculations, digital microprocessors, and high performance A/D converters to calculate the load current.
5. Analysis and design of sophisticated power electronics devices for high efficiency and fast operation of filters.

# APPENDICES

## Appendix A

### A-1.1 Harmonics

The term harmonic originates from acoustics, where it signifies the vibration of a string or a column of air at a frequency which is a multiple of the basic repetition (or fundamental) frequency. Similarly with electrical signals, a harmonic is defined as the content of a signal whose frequency is an integer multiple of the actual system frequency, i.e. the main frequency produced by the generators.

Harmonics are currents or voltages with frequencies that are integer multiples of the fundamental power frequency. For example, if the fundamental power frequency is 60 Hz then the 2nd harmonic is 120 Hz, the 3rd is 180 Hz etc. In modern test equipment, harmonics can be measured up to the 63rd harmonic. When harmonic frequencies are prevalent, electrical power panels and transformers become mechanically resonant to the magnetic fields generated by higher frequency harmonics. When this happens, the power panels or transformer vibrates and emits a buzzing sound for the different harmonic frequencies measured in electrical distribution system.

Harmonics are caused by modern electronic equipments such as personal or notebook computers, laser printers, fax machines, telephone systems, stereos, radios, TVs, adjustable speed drives and variable frequency drives, battery charges, UPS, and any other equipments powered by switched mode-power supply (SMPS) equipment. The above-mentioned electronic SMPS equipments are often referred to as non-linear loads. This type of non-linear loads or SMPS equipments generate the very harmonics they're sensitive to. SMPS equipments typically form a large portion of the electrical non-linear load in the most electrical distributing systems. There are basically two types of non-linear loads: single-phase and three-phase. Single-phase non-linear loads are prevalent in modern office buildings while three-phase loads are widespread in factories and industrial plants.

### A-1.2 Basic Facts About Harmonic Analysis

In 1822, French mathematician Jean Babtiste Joseph Fourier, postulated that any continuous function repetitive in an interval T can be represented by the summation of a fundamental sinusoidal component with a series of higher order harmonic components at frequencies which are integer multiples of the fundamental frequency.

Harmonic analysis is the process of calculating the magnitude and phases of the fundamental and higher order harmonics of the periodic waveform. The resulting series is known as Fourier series and establishes a relationship between a time domain function and that function in the frequency domain.

#### A-1.2.1 Periodic Function

A function is said to be periodic if it is defined for all real t and if there is some positive number T such that

$x(t + T) = x(t)$ for all t. ..............................(A-1)

T is called the period of the function which can be represented by the periodic repetition of the waveform at intervals T as shown in the figure. If k is any integer then it follows that

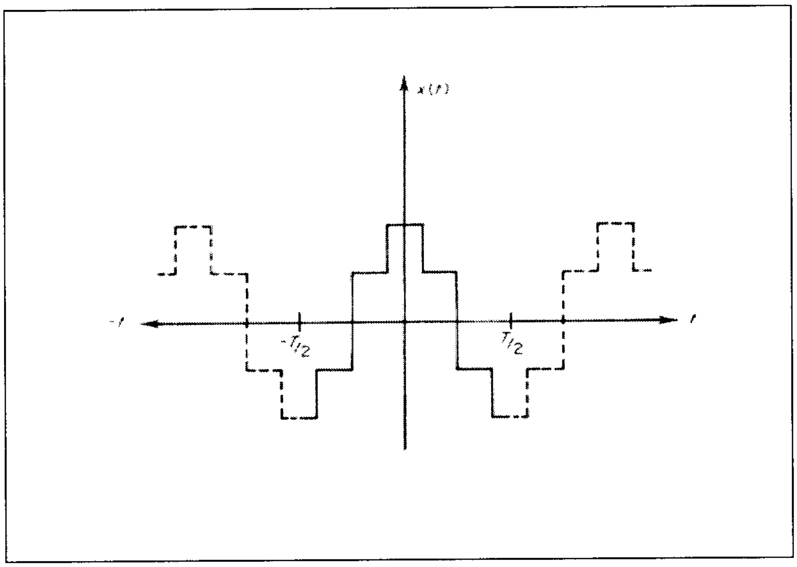


Figure A-1. Periodic Function.

$$x(t + kT) = x(t) \quad \text{for all } t. \qquad \text{(A-2)}$$

if two functions $x_1(t)$ and $x_2(t)$ have the same period T, then the function

$$x_3(t) = ax_1(t) + bx_2(t) \qquad \text{(A-3)}$$

where a and b are constants, also has the period T. And the function

$$x(t) = \text{constant} \qquad \text{(A-4)}$$

is also a periodic function in the sense of the definition, because it satisfies the above equation (A-2) for any positive T.

### A-1.3 History of Harmonic Analysis

Power system distortion has been a concern of power system engineers from early days of alternating current.

In the late 1800's and early 1900's electrical distribution practices were developed to meet the requirements of then state-of-the art equipment. Lights, motors and resistive heating elements were the devices that used electricity. By the 1920's electricity use was quite sophisticated. Polyphase distribution, multiple pole devices, rectification, phase-angle-control via vacuum tubes were used in large industrial facilities, and electrical engineering texts of that era placed a great deal of emphasis on the characteristics of these loads. Mutual induction, harmonics and power factor were well known. However, the effects of harmonics were usually the concern of electrical utilities and large industries such as smelting and metal processing. Lights, motors and heating elements used to be the major commercial loads.

Over the past two decades the composition of electrical loads in normal commercial facilities have been changed because of the extensive use of the electronic equipments and government's mandatory energy conservation policies. Personal computers have replaced typewriters, and induction motors have been replaced by electronic ballasts, lighting control dimmers and variable speed drives. In Germany, during 1920s and 1930's, the subject of waveform distortion caused by static converters was developed. And during the 1950s and 1960s the study of converter harmonics was advanced in the field of high voltage direct current transmission.

### A-1.3.1 History of Harmonic Analysis by Computer Analysis

Various computer programs have been developed for the analysis of harmonics in power systems. These computer programs perform harmonic flow analysis in the steady state because the analysis in time domain is more time consuming.

Before the widespread use of computers, power system harmonic studies were usually performed on analog simulators such as Transient Network Analyzer (TNA). TNA were in use in the United States in the mid 1970s at big equipment manufacturing companies like General Electric, Westinghouse Electric and McGraw-Edison Power System. Because of the high cost and inconvenience harmonic studies were performed only on special and critical application such as arc furnace which is a very significant candidate for the harmonic disturbance in the power system.

In 1975, Roger Dugan, then with the McGraw-Edison, constructed the first electronic arc model for TNA. To overcome the limitations of harmonic analysis by analog simulator, the team of Dugan, Dr. Sarosh N. Talukdar and William L. Sponsler at McGraw-Edison, developed one of the first commercial computer programs specifically designed to automate analysis of harmonic flows on large-scale power systems. Network Frequency Response Analysis program known as NFRAP was developed for the Virginia Electric and Power Company to study the impact of adding 220 kV capacitor bank on the transmission system. NFRAP used the direct nodal admittance matrix solution techniques. From 1977 to1979, EPRI sponsored an investigation of harmonics on utility distribution feeders. One of the products of this research was the Distribution Feeder Harmonic Analysis Program which was the first program designed specifically to analyze harmonics on unbalanced distribution system and had specific models of power system elements to help the user develop models.

The next generation of the software tool based on the NFRAP program methodology was the McGraw-Edison Harmonic Analysis Program (MEHAP) under development from 1980 to 1984. It was written in FORTRAN for minicomputers and had the distinction of being interactive with graphical output.

At the same time, Erich W. Gunther recoded the algorithms in the Pascal language and created the V-HARM® program. He has written the latest generation in the heritage of harmonic analysis tools in the C++ language for Microsoft® Windows™ environment which is called SuperHarm™ Program. The Harmonic analysis program called CYMHARMO™ was developed at Institute de Recherche d'Hydro-Qubec (IREQ) in Montreal in 1983. Since 1981, EPRI has sponsored the development of the HARMFLO program which takes a different approach to the network solution.

Of course, harmonics problem can be solved on transient analysis programs such as EMTP, originally developed by the Bonneville Power Administration. The special-purpose programs are generally more efficient for normal problems, but occasionally, a very difficult problem will be encountered that requires the simulation in the time domain.

## A-2.1 Sources of Harmonics

### A-2.1.1 Linear and Non-Linear Loads

A linear element in a power system is a component in which the current is proportional to the voltage. The current wave shape will be same as the voltage wave shape. Some typical examples of linear loads include motors, heaters and incandescent lamps.

In case of non-linear loads, the current wave shape will not be same as the voltage wave shape. Typical examples of non-linear loads include rectifiers (power supplies, UPS units, discharge lighting), adjustable speed motor drives, ferromagnetic devices, DC motor drives and arcing equipment.

Non-linear loads draw non-sinusoidal current which is periodic in nature. Periodic waveforms can be described mathematically as a series of sinusoidal waveforms that have been summed together.

Sinusoidal components are integer multiples of the fundamental (60 Hz). Each term in the series is referred to as a harmonic of the fundamental. A symmetrical wave is the one in which positive portion of the wave is identical to the negative portion. Symmetrical wave contains only odd harmonics. Un-symmetrical wave contains a DC component and positive portion of the wave is different than the negative portion. Un-symmetrical wave contains even and odd harmonics. Half-wave rectifier would be an example of un-symmetrical wave.

Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset. There are exceptions, of course, and normally symmetrical devices may produce even harmonics due to component mismatches or failures. Arc furnaces are common source of even and odd harmonics at different stages of the process.

Harmonics are caused by non-linear loads attached to power systems. Non-linear loads draw non-sinusoidal current. Resistors, inductors and capacitors are linear devices. When the loads consisting of these linear devices are applied to an AC power system, they draw sinusoidal current. The major sources of harmonics are convertors. They range from 1000MW inverter station for a HVDC line to a small 75 W rectifier used in television. Arcing devices such as arc furnaces, transformer magnetizing impedances, and fluorescent lights are the few examples of other non-linear sources. These devices are responsible for the harmonic distortion in the system voltage because of the harmonic current they draw. This harmonic current can cause problems for other devices also.

Personal computers, video display equipment, uninterruptible power sources, electronic ballast, microwave oven, silicon controlled rectifier (SCR), triac controlled lighting, variable speed drives, and elevators are the sources of harmonic current in normal commercial environments.

In medical environments, in addition to all normal commercial sources, other specialized instrumentation provides additional harmonic current. X-ray, cardio-axial-thermography, and magnetic resonance equipment are potential sources of harmonic current. Some electrical environments contain even greater concentrations of equipment which generate harmonic currents. Semiconductor fabrication facility is a good example of this category that uses great amounts of power.

6-pulse phase angle controlled supplies, 6-pulse rectified supplies, stepper motors and voltage doublers are the commonly used equipments in industrial facilities. In other words, majority of electronic equipments are the sources of harmonic current. With the increase of these instruments or equipments within the facilities, their impact upon the power system distribution system also increases.

### A-2.1.2 Controlled Rectifiers

The main sources of harmonic current at present are the phase angle controlled rectifiers and invertors which are classified according to the different harmonic characteristics.

1. Large power convertors such as those used in the metal reduction industry and high voltage d.c. transmission.

2. Medium size convertors such as those used in manufacturing industry for motor control and also in railway applications.

3. Low power rectification from single-phase supplies such as television sets and battery charges.

The largest application of static converters is in adjustable-speed drives for motor control. These static drives are now used in different types of industrial motors, providing higher efficiencies, better speed control, and more maintenance-free operation compared to the conventional motor drives.

Current waveform and harmonic spectrum for different harmonic sources are as shown below.

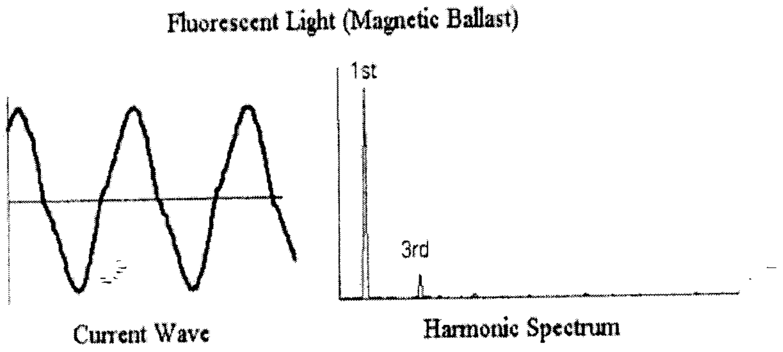


Figure A-2.1. Current waveform and harmonic spectrum of fluorescent light.

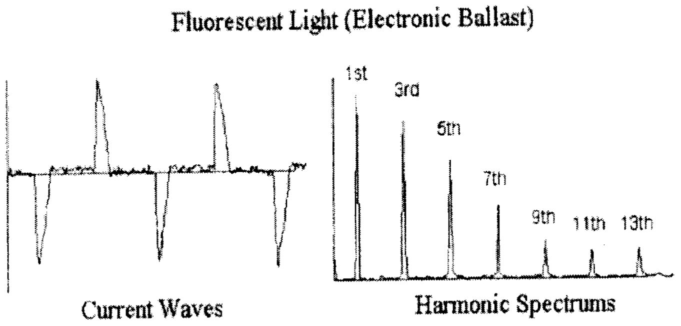


Figure A-2.2. Current waveform and harmonic spectrum of fluorescent light.

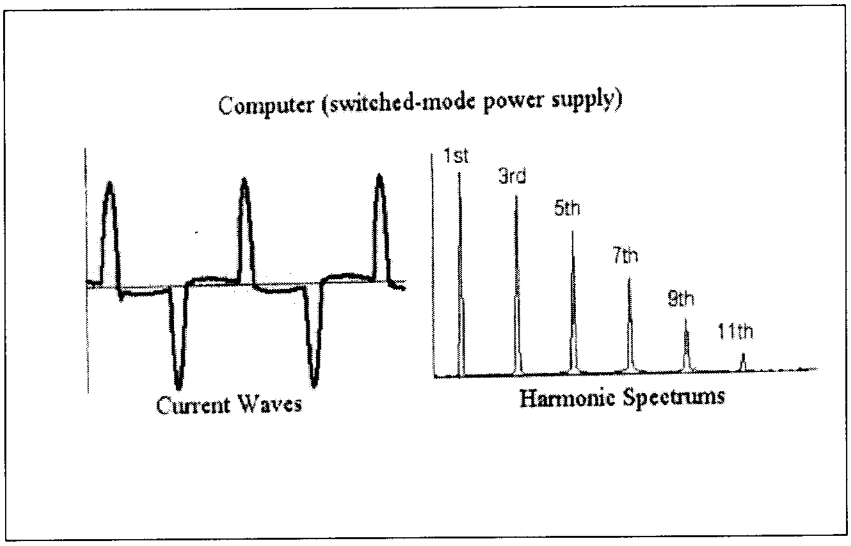


Figure A-2.3. Current waveform and harmonic spectrum of SMPS.

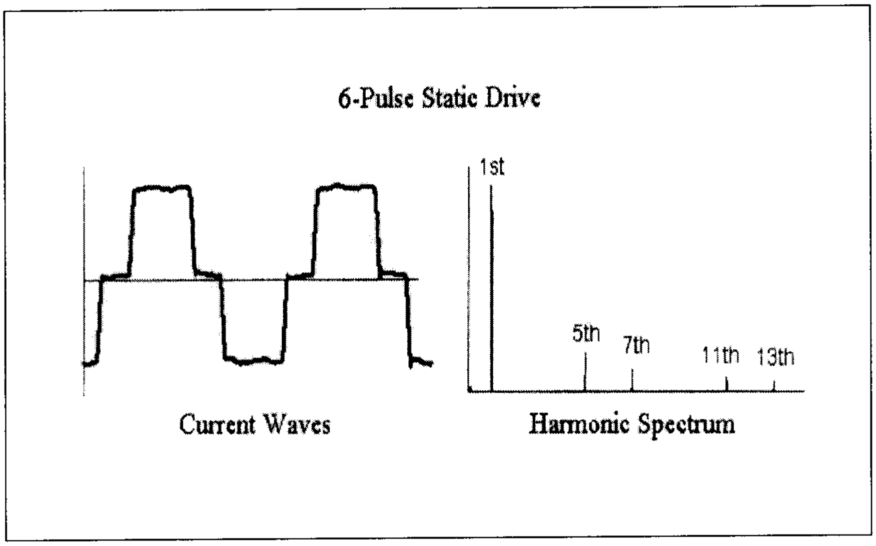


Figure A-2.4. Current waveform and harmonic spectrum of 6-pulse drive.

A single phase, full wave rectifier shown in Figure A-2.5 is the most commonly used device in all kinds of electronics devices like televisions, computers, stereos, etc. The diodes act to flip the negative half of the sine wave over. The capacitor tries to hold the voltage at the peak. The capacitor is charged up two times per cycle and this is the only time the rectifier draws current from the system. The load current is drawn in short pulses as shown in Figure A-2.6.

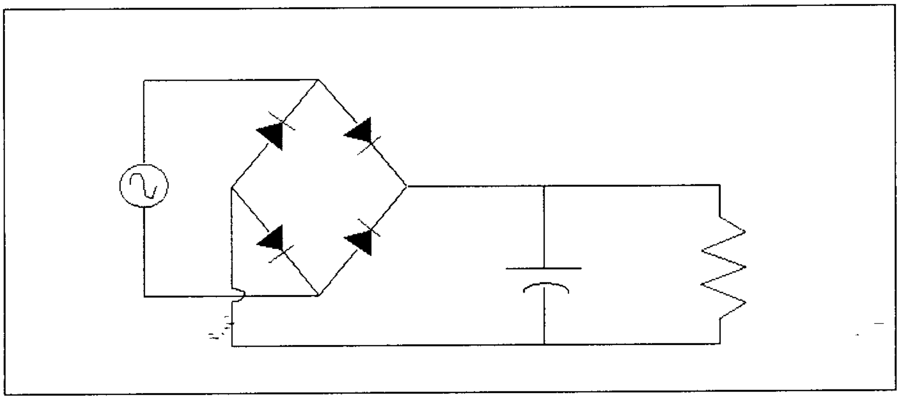


Figure A-2.5. Single-phase full wave rectifier circuit.

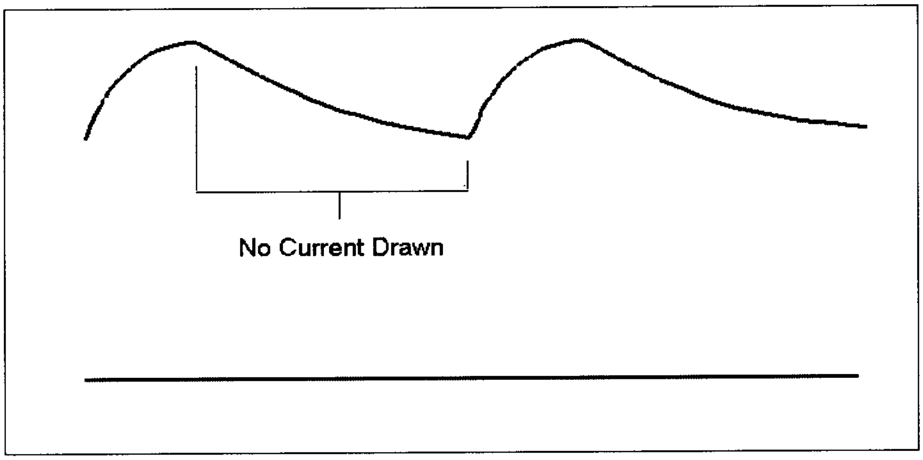


Figure A-2.6. AC current and voltage across the load in a full wave rectifier.

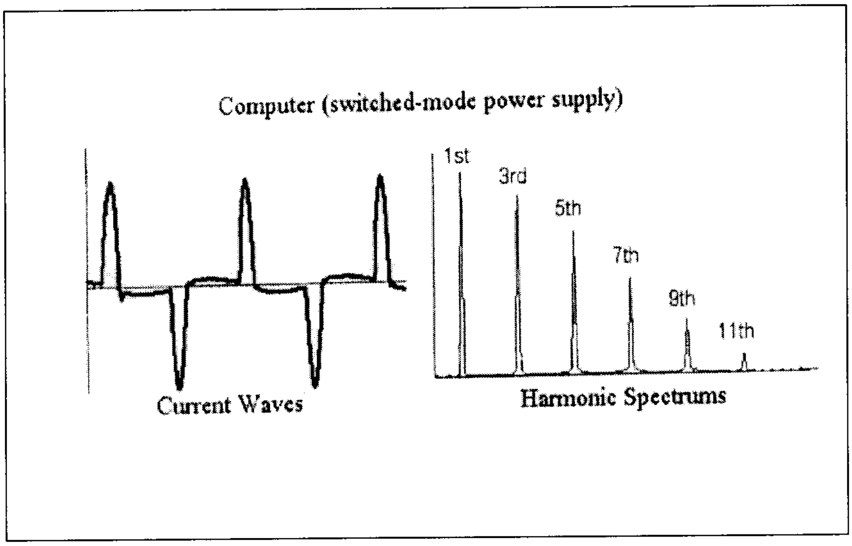
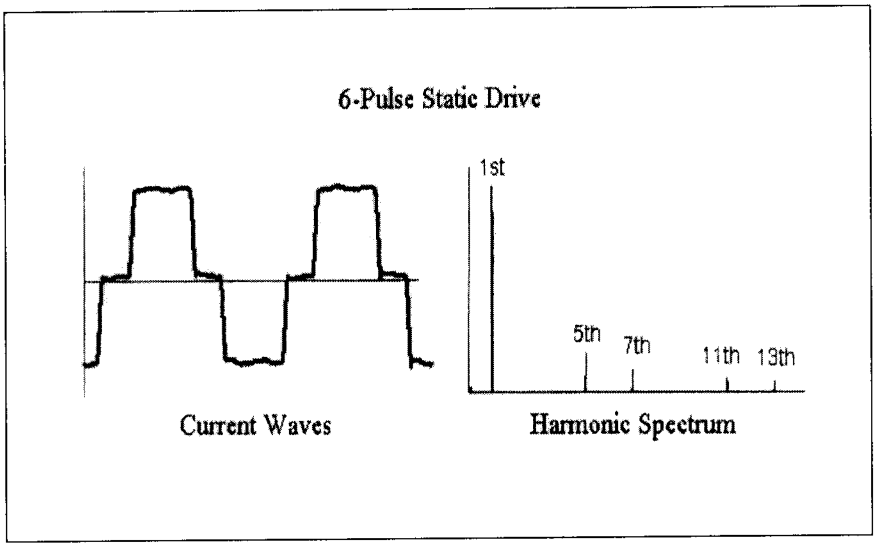


Figure A-2.3. Current waveform and harmonic spectrum of SMPS.



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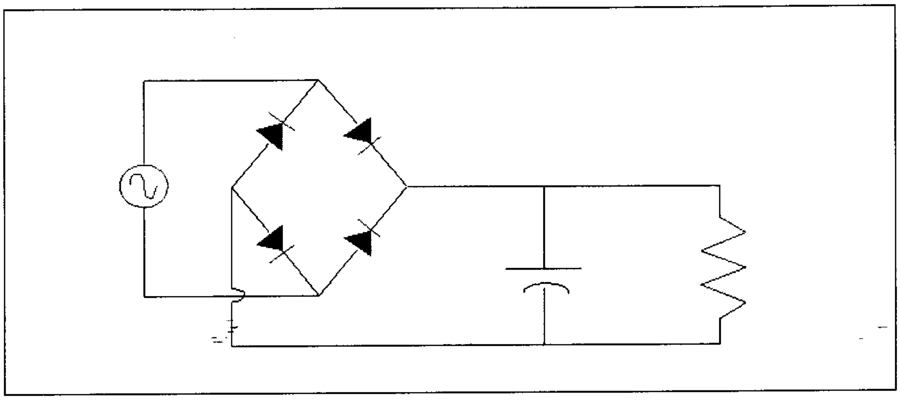

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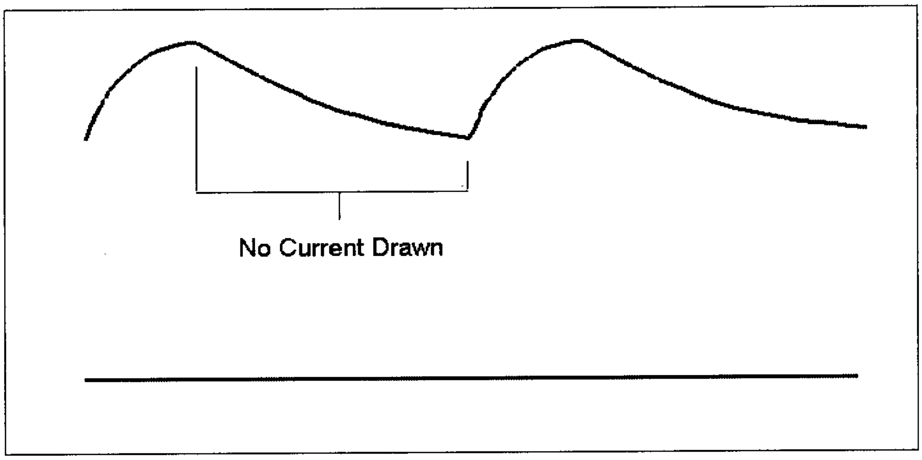


Figure A-2.6. AC current and voltage across the load in a full wave rectifier.

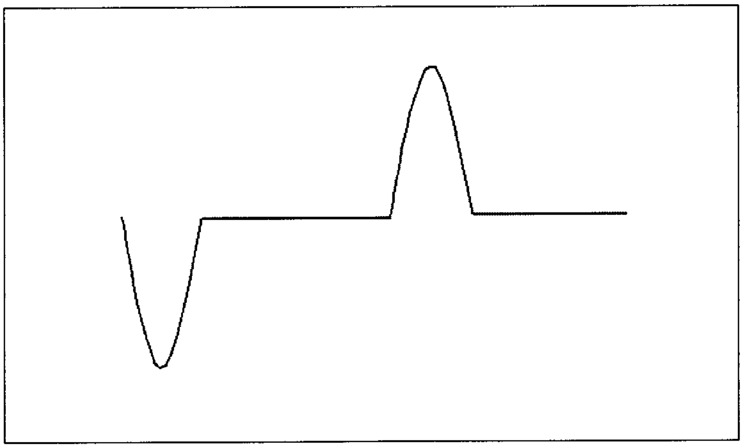


Figure A-2.7. AC current drawn by consumer equipments.

The Figure above shows AC current drawn by consumer equipments.

### A-2.2 Harmonic Injection

A polluting load, such as rectifier or variable speed drive, has the characteristics of drawing a non-sinusoidal current from a sinusoidal voltage source. Using Fourier analysis the current drawn from the supply may be split into its fundamental and harmonic components. This load may be represented as a harmonic current source "injecting" into the power system. The harmonic current will propagate into the system and react with the network impedance to cause harmonic voltage to appear. For any given study multiple injection points may be specified at different voltages and locations across the network. The harmonic characteristics are stored as user specified library elements. The program calculates total harmonic voltage and current distortion across the system as well as the individual harmonic voltage and current value.

Steady-state, linear circuit solution techniques are used for the harmonic analysis. Harmonic sources, which are nonlinear elements, are generally considered to be injection sources into the linear network models. In most of the cases, harmonic sources are treated as simple sources of harmonic current. Value of the injected current can be determined by the measurements. In the absence of that it is common to assume that the harmonic content is inversely proportional to the harmonic number. For example, the fifth harmonic current is one-fifth or 20% of the fundamental, etc. When the system is near resonance, a simple current source model will give an excessively high prediction of voltage distortion. Resonance can be eliminated by adding filter or filters.

# Appendix B

## B-1 IEEE Standards for Harmonic Currents and Voltages

### B-1.1 Introduction

Power system problems associated with harmonics began to be of general concern when two developments namely oil embargo and low voltage thyristor technology took place. Industrial consumers and utilities began to apply power factor improvement capacitors. Capacitors reduce MVA demand from the utility grid systems by supplying the reactive power portion of the load locally. As a result, losses are reduced in the industrial plant and the utility network. The move to power factor improvement resulted in a significant increase in the number of capacitors connected to power systems. As a consequence, there has been an equally significant increase in the number of tuned circuits in plant and utility networks.

Similarly, in the 1960s, thyristors were developed for dc motor drives and then extended to include adjustable-speed ac motor drives in the 1970s. This resulted in a proliferation of small, independently operated converters usually without harmonic mitigation techniques employed.

American standards regarding harmonics have been laid out by the IEEE 519 Standard: IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. There is a combined effect of all nonlinear loads on utility systems that have a limited capability to absorb harmonic current. Further, utilities are charged with the responsibility to provide a high quality supply in terms of voltage level and waveform. IEEE 519 recognizes not only the absolute level of harmonics produced by an individual source but also their size relative to the supply network.

It should be noted that IEEE-519 is limited to being a collection of Recommended Practices that serve as a guide to both suppliers and consumers of electrical energy. Problems exist because of excessive harmonic current injection or excessive voltage distortion. It is a responsibility of a supplier and a consumer to resolve the issues within a mutually acceptable framework.

The purpose of IEEE-519 is to recommend limits on harmonic distortion according to two distinct criteria, namely:

1. There is a limitation on the amount of harmonic current that a consumer can inject into a utility network
2. A limitation is placed on the level of harmonic voltage that a utility can supply to a consumer.

### B-1.2 Guidelines for Individual Customers

The primary limit on individual customers is the amount of harmonic current they can inject into the utility network. The current limits are based upon the size of the consumer relative to the size of the supply. Larger customers are restricted more than smaller customers. The relative size of the load with respect to the source at the point of common coupling (PCC) is defined as the short circuit ratio (SCR). PCC is the point where the consumer's load connects to other loads in power systems. The consumer's size is defined by the total fundamental frequency current in the load, $I_L$, which includes all linear and nonlinear loads. The size of the supply system is defined by the level of short-circuit current, $I_{SC}$, at the PCC. These two currents define the SCR given by

$$\text{SCR} = \text{short circuit MVA} / \text{load MW} = I_{SC} / I_L \quad \text{(B-1)}$$

A high ratio of SCR means that the load is relatively small. This is demonstrated in table 3, which lists recommended, maximum current distortion levels as a function of SCR and harmonic order. The table also identifies total harmonic distortion levels. All of the current distortion values are given corresponding to the maximum demand load current. The total distortion is in terms of total demand distortion (TDD) instead of the more common total harmonic distortion (THD) term.

Table 3 shows current limits for individual harmonic components as well as total harmonic distortion. For example, a consumer with a SCR between 50 and 100 has a recommended limit of 12.0% for TDD, while for individual odd harmonic components with orders less than 11, the limit on each is 10%.

### B-1.3 IEEE-519 Current Distortion Limits

Table 3. IEEE-519 Current Distortion Limits

*For conditions lasting more than one hour. Shorter periods increase limit by 50%)*

**Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages 120 - 69,000 volts**

Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order

| $I_{SC}/I_L$ | $<11$ | $11 \le h < 17$ | $17 \le h < 23$ | $23 \le h < 35$ | $35 \le h$ | TDD |
|---|---|---|---|---|---|---|
| <20* | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20<50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50<100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100<1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

**Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages > 69,000 - 161,000 volts**

Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order

| $I_{SC}/I_L$ | $<11$ | $11 \le h < 17$ | $17 \le h < 23$ | $23 \le h < 35$ | $35 \le h$ | TDD |
|---|---|---|---|---|---|---|
| <20* | 2.0 | 1.0 | 0.75 | 0.3 | 0.15 | 2.5 |
| 20<50 | 3.5 | 1.75 | 1.25 | 0.5 | 0.25 | 4.0 |
| 50<100 | 5.0 | 2.25 | 2.0 | 0.75 | 0.35 | 6.0 |
| 100<1000 | 6.0 | 2.75 | 2.5 | 1.0 | 0.5 | 7.5 |
| >1000 | 7.5 | 3.5 | 3.0 | 1.25 | 0.7 | 10.0 |

**Harmonic Current Limits for Non-Linear Load at the Point-of-Common-Coupling with Other Loads, for voltages >161,000 volts**

Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order

| $I_{SC}/I_L$ | $<11$ | $11 \le h < 17$ | $17 \le h < 23$ | $23 \le h < 35$ | $35 \le h$ | TDD |
|---|---|---|---|---|---|---|
| <50 | 2.0 | 1.0 | 0.75 | 0.30 | 0.15 | 2.5 |
| >50 | 3.0 | 1.5 | 1.15 | 0.45 | 0.22 | 3.75 |

Even harmonics are limited to 25% of the odd harmonic limits above.

*All power generation equipment is limited to these values of current distortion, regardless of actual $I_{SC}/I_L$.

Where $I_{SC}$ = Maximum short circuit current at point-of-common-coupling.
And $I_L$ = Maximum demand load current (fundamental frequency) at point of common coupling.
TDD = Total demand distortion (RSS) in % of maximum demand

### B-1.4 Transformer Heating

The distortion limits given in table 3 are only permissible provided that the transformer connecting the user to the utility system will not be subjected to harmonics in excess of 5% of the transformers rated current as stated in ANSI/IEEE C57.12.00-1980.

### B-1.5 Guidelines for Utilities

The second set of criteria established by IEEE-519 is for voltage distortion limits. This governs the amount of voltage distortion that is acceptable in the utility supply voltage at the PCC with a consumer. The harmonic voltage limits recommended are based on levels that are low enough to ensure that consumers' equipment will operate satisfactorily.
Table 4 lists the harmonic voltage distortion limits from IEEE-519.

### B-1.6 Voltage Distortion Limits from IEEE-519

Table 4. Voltage Distortion Limits from IEEE-519
*(For conditions lasting more than one hour. Shorter periods increase limit by 50%)*

| Bus Voltage at Point of Common Coupling | Individual Voltage Distortion (%) | Total Voltage Distortion THD (%) |
|---|---|---|
| Below 69 kV | 3.0 | 5.0 |
| 69 kV to 137.9 kV | 1.5 | 2.5 |
| 138 kV and above | 1.0 | 1.5 |

Table 4 shows IEEE-519, 1992 voltage distortion limits. They represent three voltage levels: up to 69 kV, 69 to 161 kV, and equal to or greater than 161 kV. The limits decrease as voltage increases. Only odd harmonic limits are shown in the table. The generation of even harmonics is more restricted since the resulting dc offset can cause saturation in motors and transformers. Negative sequence current can cause heating in generators. Individual even harmonic voltage is limited to 25% of the odd harmonic limits. Utility feeders supply more than one consumer. The voltage distortion limits shown in the table should not be exceeded as long as all consumers conform to the current injection limits. Any consumer who degrades the voltage at the PCC should take steps to correct the problem. However, the problem of voltage distortion is one for the entire community of consumers and the utility. Large consumers may look for a compromise with the utility over resolution of a specific problem, and both may contribute to its solution.

# Appendix C

## C-1 Important Topics of Power System in Harmonic Analysis

### C-1.1 Per Unit System

Power transmission lines are operated at voltage levels where the kilovolts is the most convenient unit to express voltage. Kilowatts or megawatts and kilovoltamperes or megavoltamperes are the common terms used to represent the transmission line parameters because of the large amount of power transmitted. Nevertheless, in addition to these quantities amperes and ohms are usually expressed as a percent or per unit of a base or reference value specified. For example, if a base voltage of 120 kV is chosen, voltages of 108, 120, and 126 becomes 0.90, 1.00, and 1.05 per unit or 90, 100, and 105% respectively. The per-unit value of any quantity is defined as the ratio of the quantity to its base value. Both the percent and per-unit methods of calculation are simpler than the use of the actual amperes, ohms, and volts. The per unit method has an advantage over the percent method because the product of two quantities expressed in per unit must be divided by 100 to obtain the result in percent.

The formulas for the base values are as follows.

Base current, A = base $kVA_{1\Phi}$ / base voltage, $kV_{LN}$........................(C-1)

Base impedance = base voltage, $V_{LN}$ / base current, A...................(C-2)

Base impedance = (base voltage, $kV_{LN})^2$ * 1000 / base $kVA_{1\Phi}$.........(C-3)

Base impedance = (base voltage, $kV_{LN})^2$ / base $MVA_{1\Phi}$.................(C-4)

Base power, $kW_{1\Phi}$ = base $kVA_{1\Phi}$...........................................(C-5)

Base power, $MW_{1\Phi}$ = base $MVA_{1\Phi}$.........................................(C-6)

Hence, the Per-unit impedance of a circuit element is given by

actual impedance, Ω / base impedance, Ω.

The subscripts $1\Phi$ and LN denote "per phase" and "line-to-neutral" respectively, where the equations apply to three-phase circuits. If the equations are used for a single-phase circuit, $kV_{LN}$ means the voltage across the single-phase line, or line-to-ground voltage if one side is grounded.

Incase of three-phase system,

Base current, A = base $kVA_{3\Phi} / \sqrt{3} * \text{base voltage}, kV_{LL}$......................(C-7)

Base impedance = $(\text{base voltage}, kV_{LL} / \sqrt{3})^2 * 1000 / \text{base } kVA_{3\Phi} / 3$......(C-8)

Base impedance = $(\text{base voltage}, kV_{LL})^2 * 1000 / \text{base } kVA_{3\Phi}$..............(C-9)

Base impedance = $(\text{base voltage}, kV_{LL})^2 * \text{base } MVA_{3\Phi}$.....................(C-10)

## C-1.2 Symmetrical Components

Symmetrical components are used in analyzing three-phase system behavior. Three-phase system is transformed into three single-phase system for the purpose of simpler analysis. The methods of symmetrical components can be used for analysis of the system's response to harmonic currents without violating the fundamental assumptions of the method. This method permits any unbalanced set of phase currents or voltages to be transformed into three balanced sets. The positive sequence set contains sinusoids displaced 120 degrees from each other with the normal A-B-C phase rotation. The sinusoids of negative sequence sets are displaced 120 degrees but have opposite phase rotation (A-C-B). The zero sequence sinusoids are in phase with each other.

For balanced systems:

- 1st, 7th, 13th, ...........order harmonics are purely of positive-sequence,
- 5th, 11th, 17th, .........order harmonics are purely of negative-sequence and
- 3rd, 9th, 15th.... ........order harmonics are of purely zero sequence.

In case of the balanced system, triplen and zero-sequence are same. When there is a delta winding in a transformer anywhere in series with the harmonic source and the power system, only the positive-sequence circuit needs to be represented to determine the system response. Since zero-sequence harmonics are blocked it is impossible for them to be present. Both the positive and negative-sequence networks generally have the same response to harmonics.

We can analyze many harmonic cases using symmetrical component modeling techniques. In the case of three-phase industrial loads, nearly all such loads can be analyzed using the positive-sequence impedance model. Exceptions are harmonics from single-phase loads on utility distribution feeders and 120/208 V circuits in industrial and commercial buildings.

### C-1.3 System and Capacitor Impedance

The importance of the system response in power system is as equal as harmonic sources. It is very essential to find out the system impedance at each frequency that determines the true impact of nonlinear load on harmonic voltage distortion.

At the fundamental frequency, power systems are primarily inductive, and the equivalent impedance is called the "short-circuit impedance". Capacitive effects are frequently neglected on utility distribution systems and industrial power systems. Short circuit impedance is more commonly used in the harmonic analysis of the power system. The short circuit impedance is given by

$$Z_{SC} = R_{SC} + j\,X_C \quad = kV^2 / MVA_{SC} = I_{SC} / \sqrt{3}\ kV \ \ldots\ldots\ldots\ldots\ldots\ldots(C\text{-}11)$$

where,
$Z_{SC}$ = short-circuit impedance,
kV = phase-to-phase voltage, kV,
$R_{SC}$ = short-circuit resistance,
$MVA_{SC}$ = three-phase short circuit MVA,
$X_C$ = short-circuit reactance,
$I_{SC}$ = short-circuit current, A.

The reactance at the h^th harmonic is determined from the fundamental-impedance reactance, $X_1$, by

$$X_h = h\,X_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(C\text{-}12)$$

### C-1.4 Capacitor Impedance

Shunt capacitors, either at the customer location for power factor correction, or on the utility distribution system, alter the system impedance variation with frequency. The presence of capacitors can result in the severe harmonic distortion, however, they do not create harmonics by themselves.

Capacitive reactance is given by

$$X_C = 1 / 2\,\pi\,f\,C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(C\text{-}13)$$

where, C is the capacitance in Farad.

However, this $X_C$ is not easily available for power capacitors which are rated in terms of kVAR and MVAR at a given voltage.

The equivalent line-to-neutral capacitive reactance at a fundamental frequency for a capacitor bank can be determined by

$$X_C = kV^2 / MVAR = kV^2 (1000) / kVAR \qquad \text{(C-14)}$$

In case of 3-phase system, phase-to-phase voltage and three-phase reactive power rating should be used.

### C-1.5 Power Factor

The total electrical power (KiloVoltAmperes or KVA) used by the industrial or commercial facility has two components:

- Real or Productive Power (Kilowatts or KW) which produces work.
- Reactive Power (Kilovar or KVAR) which generates the magnetic fields needed in inductive electrical equipment (transformers, AC motors, inductive furnaces etc.).

Inductive electrical equipment employing magnetic fields requires reactive power, which does not result in any productive work. The total power (KVA) provided by the generating source must be greater than the productive power.

Power factor is the ratio of real power (KW) to the total power (KVA). Power factor can be expressed as the measure of system electrical efficiency in an alternating current circuit, and is represented as a percentage (%) or a decimal.

The relationship between KVA, KW, and KVAR is non-linear and is given by

$$KVA^2 = KW^2 + KVAR^2 \qquad \text{(C-15)}$$

Power factor can be improved by removing the system KVAR which reduces the utility power bills. Similarly, power factor improvement results in the increase of the system capacity and permits additional loads (motors, lighting, etc.) to be added without overloading the system.

#### C-1.5.1 Harmonic Distortion and Power Factor Correction

Developments in semi-conductor technology have created a major increase in thyristor and converter-fed loads. Electronic equipment, particularly that using solid state devices, can have a detrimental effect in electrical power systems. Solid state devices generate harmonics into the electrical system, i.e. they generate frequencies that are integer multiples of the fundamental line frequency of 60 Hz. The harmonics lead to a higher capacitor current, because the higher frequencies are attracted to the capacitor. The impedance of the capacitor decreases as the frequency increases.

Harmonic distortion can result in any or all of the following:

- Premature failure of capacitors.
- Nuisance tripping of circuit breakers and other protective devices.
- Failure or malfunctioning of computers, motor drives, lighting circuits and other sensitive loads.

The rising capacitor current can be accommodated by design improvements of the capacitor. However, resonating circuit may occur between the power factor correction capacitors and the inductance of feeding transformer as well as the main feeders. If the frequency of such a resonating circuit is close enough to the harmonic frequency, the resulting circuit amplifies the oscillation and leads to immense over-currents and over-voltages.

### C-1.5.2 Tuned Filter Capacitor Banks or Harmonic Filter

Filter circuit presents very-low impedance to the individual harmonic current, diverting the majority of the current into the filter bank rather than into the supply. The resonance frequency of a detuned capacitor is always below the frequency of the fifth harmonic.

### C-1.5.3 De-Tuned Capacitor Banks

Installation of detuned (reactor-connected) capacitors is designed to force the resonant frequency of the network below the frequency of the lowest harmonic present. This ensures that no resonant circuit exists and there will be no amplification of harmonic currents. Such an installation has a partial filtering effect reducing the level of voltage distortion on the supply, and is recommended for all cases where the share of harmonic-generating loads is more than 20% of overall load.

## C-2 Generation

An electric-power generator's primary function is to convert fuel (or the other resource) into electric power. Almost all generators have considerable control over their terminal voltage and reactive-power output. The ability of a generator to provide reactive support depends on its real-power production. Like most electric equipment, generators are limited by their current-carrying capacity. Near rated voltage, this capability becomes an MVA limit for an armature of the generator rather than a MW limitation. Absorption of reactive power is limited by the magnetic-flux pattern in the stator, which results in excessive heating of the stator-end iron. The synchronizing torque is also reduced when absorbing large amounts of reactive power which limits generator capability to reduce chance of losing synchronism with the system.

## C-3 Synchronous Condensers

Every synchronous machine, motor or generator, has reactive-power capabilities. Synchronous motors are occasionally used to provide voltage support to the power system as they provide mechanical power to their load. Some combustion turbines and hydro units are designed to allow the generator to operate without its mechanical power source simply to provide the reactive-power capability to the power system. Synchronous machines designed exclusively to provide reactive support are called synchronous condensers. Synchronous condensers have all of the response speed and controllability advantages of generators without the need to construct the rest of the power plant (e.g., fuel-handling equipment and boilers). They also consume real power equal to about 3% of the machine's reactive-power. A 50-MVAR synchronous condenser requires about 1.5 MW of real power.

## C-4 Capacitors and Inductors

Capacitors and inductors are passive devices that generate or absorb reactive power. They accomplish this without significant real-power losses or operating expense. The output of capacitors and inductors are proportional to the square of the voltage. Thus, a capacitor bank (or inductor) rated at 100 MVAR will produce (or absorb) only 90 MVAR when the voltage dips to 0.95 per unit but it will produce (or absorb) 110 MVAR when the voltage rises to 1.05 per unit. This relationship is helpful when inductors are employed to hold voltages down. The inductor absorbs more reactive power when voltages are at the highest level. The relationship is unfortunate for the more common cases where capacitors are employed to support voltages. In the extreme cases, voltages fall, and capacitors contribute less, resulting in a further degradation in voltage. Inductors are discrete devices designed to absorb a specific amount of reactive power at a specific voltage. They can be switched on or off but offer no variable control. Capacitor banks are composed of individual capacitor cans. The cans are connected in series and parallel to obtain the desired capacitor-bank voltage and capacity rating. Like inductors, capacitor banks are discrete devices but they are often configured with several steps to provide a limited amount of variable control.

## C-5 Static Var Compensators (SVCs)

A Static Var Compensators (SVC) combines conventional capacitors and inductors with fast switching capability. Switching takes place in the subcycle timeframe (in less than 1/60 of a second), providing a continuous range of control. The range can be designed to span from absorbing to generating reactive power. Consequently, the controls can be designed to provide very fast and effective reactive support and voltage control.

SVCs use capacitors and suffer from degradation in reactive capability as voltage drops. They do not have the short-term overload capability of generators and synchronous condensers. SVC applications usually require harmonic filters to reduce the amount of harmonics injected into the power system.

# Appendix D

## D-1 Terms and Definitions Used in Harmonic Analysis

- **Active filter:** Any number of sophisticated power electronics devices for the elimination of harmonic distortion.
- **Current distortion:** Any deviation from the normal sine wave for an ac line current.
- **Distortion:** Any deviation from the normal sine wave for an ac quantity.
- **Frequency deviation:** An increase or decrease in the power frequency. The duration of frequency deviation can be from several cycles to several hours.
- **Fault:** Generally refers to short circuit in power system.
- **Fundamental (component):** The component of order 1(60 Hz) of the Fourier series of frequency.
- **Frequency Response:** In power quality usage, generally refers to the variation of impedance of the system, or a metering transducer, as a function of frequency.
- **Harmonic (component):** A component of order greater than one of the Fourier series of a periodic quantity.
- **Harmonic (content):** The quantity obtained by subtracting the fundamental component from an alternating quantity.
- **Harmonic distortion:** Periodic distortion of the sine wave.
- **Harmonic filter:** On power systems, a device for filtering one or more harmonics from the power system. Most are passive combinations of inductance, capacitance, and resistance.
- **Harmonic number:** The integral number given by the ratio of the frequency of a harmonic to the fundamental frequency.
- **Harmonic resonance:** A condition in which the power system is resonating near one of the major harmonics being produced by non-linear elements in the system, thus exacerbating the harmonic distortion.
- **Interharmonic (component):** A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate (60 Hz).

- **Linear Load:** An electrical load device that, in steady-state operation, presents essentially constant load impedance to the power source through out the cycle of applied voltage.

- **Non-linear Load:** Electrical load which draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

- **Passive filter:** A combination of inductors, capacitors, and resistors designed to eliminate one or more harmonics. The most common variety is simply an inductor in series with a shunt capacitor, which short-circuits the major distorting harmonic component from the system.

- **Total Harmonic distortion (THD):** The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity; expressed as a percentage of the fundamental.

- **Total Demand Distortion (TDD):** The ratio of the root-mean-square of the harmonic current to the root-mean-square value of the rated or maximum demand fundamental current, expressed as a percent.

- **Triplen Harmonics:** Odd multiple of the third harmonic, which deserve special attention because of their natural tendency to be zero sequence.

- **Voltage fluctuation:** A series of voltage changes or cyclical variation of the voltage envelope.

- **Voltage imbalance:** A condition in which the three phase voltages differ in amplitude or are displaced from their normal 120 degree phase relationship or both. Frequently expressed as the ratio of the negative sequence or zero sequence to the positive sequence voltage, in percent.

- **Waveform distortion:** A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

- **Phase-shift:** The displacement in time of one voltage-waveform relative to other voltage waveform(s).

- **Power Factor (true):** The ratio of active power (watts) to apparent power (voltamperes).

- **Power Factor (displacement):** The power factor of the fundamental frequency component of the voltage and current waveforms.

## D-2 Power Tools For Windows (Database Design and Concepts)

Power Tools for Windows (PTW) is a very sophisticated graphical interface built on an object-oriented database, giving fast and reliable modeling capabilities. The following sections briefly describe the relationship between parts of the database mode and the kinds of data the database stores.

### D-2.1 Projects and Documents

PTW is a graphical interface between the projects and the documents. All power system modeling and setup data are contained either in a document or in a project.

#### D-2.1.1 Projects

Projects in PTW represent the most fundamental unit. The first thing to do after starting PTW is to open or create a project. A project is not a file or even a collection of files; it is actually a database containing all the information that is specific to a system, such as component data or attributes, electrical attributes, topology (interconnections), drawings, project options. When a project is open, that project defines the boundaries of PTW; all of the component data and drawing data accessible from within a project pertain to that project alone. Any changes to one part of the project affect the rest of the project instantaneously.

#### D-2.1.2 Documents

Documents represent containers that present data in different ways and through various interfaces. The data contained in documents varies from type to type. They contain data associated with the project. Documents can be considered as the ways of organizing, viewing and editing all of data which are necessary in building a project, running studies and analyzing the results. These are four kinds of documents in PTW.

- Component Editor: The component editor is a dynamic dialog box in which components can be created and edited. Along with the drawing, the component editor represents one of the primary network editing tools in PTW. The component editor's display can be limited and defined by running a query.
- Drawing: A drawing is similar to one-line diagram. It is in fact an interactive one-line diagram for existing projects, complete with a system and study data. Drawings are optional documents provided for those who prefer to build system graphically. Drawing objects can be selected by running a query.
- Libraries: Libraries contain default data that make defining components in the system much easier and faster. There are four kinds of libraries: Cable, Transformer, Demand Load, and Motor Center. Libraries are fully customizable, and can be entered in English and Metric Units.

- Reports: Reports are ASCII text files that contain the result of studies, input data, or notes about the project.

Some of these document types are totally internal to get the database, some are totally external and others are related to the database.

### D-2.2 Components and Attributes

Components and attributes refer to the kinds of data that can be stored in the documents described in the previous section. A component is the smallest discrete unit of data the database holds. An attribute is a characteristic or property of the component.

#### D-2.2.1 Components

The smallest discrete physical or theoretical unit of a project is called a component. Components include electrical devices such as cables, transformers, motors, generators, transmission lines, loads, and buses. One project can contain hundreds or even thousand of components.

#### D-2.2.2 Attributes

Each component contains certain characteristics such as length, rated voltage and so on. The characteristics belonging to a component depend upon the component type. For example, cables have a length associated with them, but induction motors do not. All of these characteristics are called attributes. Attributes are stored with the component so that each component can be thought of as a single object comprising a collection of attributes

## D-3 Project Editing Environments

There are two primary editing environments in PTW: the drawing and the component editor. In either of these two environments, components can be added to, connected to, or deleted from the project. The primary difference between the editing environments is the user interface.

The drawing works visually and it is more practical than the component editor. One-line drawings can be created by moving component symbols onto a drawing area and connecting them to form a network topology.

The component editor is tabular, displaying component data in the dialog box. Both editors share a common project database, and are completely interactive. If a motor is deleted from the component editor then it will be deleted from the drawings too.

### D-3.1 Component Editor

Component editor is a dynamic dialog box used primarily for entering or changing the attributes of electrical components. For instance, if a synchronous motor has been created using the drawing, detailed component data can be entered by using the component editor.

If a component is selected in the component editor box, the corresponding data appears on the right. Some components have more than one page data and its page is referred to as a subview. To switch to a different subview, the new subview can be selected from the list.

Components can be added to and deleted from the network by using the component editor. PTW simplifies this task by transferring data from connected components to the new component. If a new motor is attached to an existing bus, the motor picks up the bus voltage automatically. The components editor also controls the link to the library data.

### D-3.2 Drawing

The PTW drawing is a visual design environment for building a classic one-line diagram, but is much more powerful. Drawings are not simply drafting tools in PTW, but actual modeling tools that can be used to build power system and to analyze the results. Network topology can be created by simply selecting component symbols from a toolbar, and moving them onto the drawing area. To connect components, lines can be dragged between them.

This method of building the network simultaneously creates a network one-line diagram, and establishes component records and connections in the database. When component symbol is added to the drawing, that component is immediately available from the component editor.

### D-3.3 Queries

The term “query” is a database’s characteristic term. In its fundamental sense, a query is a limiting function that compares all of the records in a database to a set of user defined criteria, and displays only the records that meet these criteria. Each component in the project represents a single project. Each of these components has associated characteristics such as voltage, length, KVA and so on. PTW provides a sophisticated query function that helps to search any of these characteristics.

### D-3.4 Libraries

A library is a document that stores standard reference data for a particular component type. Libraries can be used to speed up the process entering data for network components. For example, power system may contain several aluminum 600V, 250 kc mil cables. Instead of having to type in all of the impedances, raceway and ground wire size data for each cable, the component editor can be used to pick the cable from library. Libraries can be customized. This will result to an exact modeling of system and consistent values for the possible calculations.

PTW includes four different types of libraries:

- Cable
- Transformer
- Demand Load
- Motor Control Center

Each of these libraries stores information for several components. The transformer library for example, stores KVA, %R and %jX data on dry type transformers, oil/air transformers and so on.

The libraries store information in a familiar spreadsheet that helps to add, copy and delete data quickly and easily. Like the component editor, the library also makes use of component subviews of devices.

### D-3.5 Studies

Studies are heart of PTW. They analyze and evaluate network and generate reports for the load flow, voltage drop, demand loads, and so on. Study manager can be used to run all studies at the same time, and to save the reports in any directory. If multiple studies are selected, PTW automatically determines the proper study sequence, and turns them in that order. Study parameters can also be edited to suit specific needs.

The studies that are available in PTW are:

- Demand Load Study
- Feeder and Transformer Sizing Study
- Load Flow Study
- Short Circuit Study
- Load Schedules

### D-3.6 Reports and Datablocks

By running the studies, tremendous amount of information can be accessed, and the information can be looked at in different ways to meet specific needs. PTW provides two principle methods of looking at study data: reports and datablocks.

### D-3.6.1 Reports

Each study type generates a pre-formatted ASCII text file report that presents an in-depth analysis of entire system. PTW automatically generates a report for every study to run. Reports are named and stored. Reports are linked interactively to the database. Each report represents a snapshot of a system at moment in time, but will not change as system parameters. Reports typically run to several pages in length and can be used for presentations and troubleshooting. But they may not always be the format for finding very specific data, or for analyzing the study results on a particular component.

### D-3.6.2 Datablocks

Using datablocks, component attributes can be set up and viewed in a unique format for each component type. Each named format can be saved in a datablock file. For instance, a datablock can be set up to display the connected kVA and the connected power factor cables. The datablock formats consist of any desired component attributes. They may consist of input data, output data, or a combination of both.

Number of named datablock formats can be created, each of which can be very simple or very complex. One datablock format might include a few data for buses alone, whereas another might include tens of data items for every available component type.

Datablock formats can be viewed in a variety of places in the PTW interface. There are two options for viewing datablock on a drawing. First, using the probe, any component can be clicked and its datablock can be seen in a temporary popup window. Second, all datablocks can be viewed on the surface of the drawing. Each three of these datablock locations can be assigned different datablock formats.

## D-4 Features: HI_WAVE

### D-4.1 General Features:

- Large libraries of feeders, transformers and harmonic sources.
- Advanced modeling techniques provide the fastest possible solution.

### D-4.2 Analysis Capabilities:

- Analysis of harmonic effects from power factor correction capacitors.
- Modeling of harmonic voltage sources or current sources at each bus.
- Graphical presentation of harmonic current and voltage distortion.
- Frequency scans for all system resonance points.
- Harmonic load flow analysis.
- Calculation of telephone interference factors (TIF, IT).
- Reports total harmonic current and voltage distortion factors (THD%) per IEEE 519 standard.
- Automatic modeling for both the positive and zero sequence networks.
- Automatic modeling of transformer connections as triplen harmonic traps.
- Calculation of non-linear frequency dependent characteristics for feeders and transmission lines.
- Calculation of non-linear frequency dependent characteristics for transformers.
- Frequency spectrum and locus plots for current and voltage distortion.
- Low pass and high pass filter design.
- Calculation K-Factor to meet proposed UL standards and ANSI C57.110 procedure

### D-4.3 Modeling Capabilities:

- All loop and radial power systems may be modeled.
- Any combination of voltage levels may be modeled.
- Aerial and ground mode modeling using Eigen-vectors.
- Automatic modeling of all standard transformer connections.
- Low pass filter modeling.
- High pass filter modeling.
- Load flow analysis including all filter and capacitor modeling.
- Demand load analysis for load scaling.
- Linear and non-linear frequency dependent modeling for cables and transmission lines.
- Non-linear frequency dependent modeling for transformers.
- Calculations include transformer phase shift.
- Calculations include harmonic source phase angles.

### D-4.4 Output Results:

- Graphical results for voltage and current wave distortion.
- Graphical results for voltage and current frequency spectrum.
- Graphical results for impedance frequency scan.
- Graphical results for locus and angle plots.
- Comparison of multiple studies on the same graph.
- Detailed reports for distortion and frequency scan.

# Appendix E

## System Input Data

**SKM POWER*TOOLS FOR WINDOWS**
**INPUT DATA REPORT**

**ALL PU VALUES ARE EXPRESSED ON A 100 MVA BASE.**

### TRANSMISSION LINE

```
FROM       TO          QTY   VOLTS       LENGTH
                             /PH L-L

BUS-0001   BUS-0002      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0002   BUS-0008      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0001   BUS-0008      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0011   BUS-0013      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0008   BUS-0013      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0023   BUS-0024      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0013   BUS-0024      1 13800.00      20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005
```

```
BUS-0024     BUS-0022          1 13800.00   20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0014     BUS-0015          1 13800.00              20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0023     BUS-0015          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0015     BUS-0018          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0018     BUS-0019          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0019     BUS-0020          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0014     BUS-0012          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0015     BUS-0012          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0017     BUS-0016          1 13800.00               20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0012     BUS-0016          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0022     BUS-0021          1 13800.00                 20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005
```

```
BUS-0020     BUS-0010          1 13800.00                  20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0017     BUS-0010          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

BUS-0021     BUS-0010          1 13800.00                20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0022     BUS-0010          1 13800.00               20.00 Miles
 + Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
 0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

 BUS-0003     BUS-0004          1  4160.00              20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0003     BUS-0030          1  4160.00              20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

 BUS-0004     BUS-0006          1  4160.00              20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0005     BUS-0006          1  4160.00                20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

 BUS-0005     BUS-0027          1  4160.00                20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

 BUS-0027     BUS-0007          1  4160.00                20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

 BUS-0004     BUS-0029          1  4160.00                 20.00 Miles
 + Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
 0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006
```

BUS-0030 BUS-0029 1 4160.00 20.00 Miles
+ Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0029 BUS-0006 1 4160.00 20.00 Miles
+ Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0029 BUS-0028 1 4160.00 20.00 Miles
+ Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0028 BUS-0007 1 4160.00 20.00 Miles
+ Seq Impedance: 5.3162 + J 13.4061 Per Unit; Equi. Shunt B: 0.000169663
0 Seq Impedance: 142.151 + J 256.564 Per Unit; Equi. Shunt B: 5.19688e-007

BUS-0006 BUS-0027 1 4160.00 20.00 Miles
+ Seq Impedance: 35.3643 + J 75.7276 Per Unit; Equi. Shunt B: 1.13188e-005
0 Seq Impedance: 68.4403 + J 336.66 Per Unit; Equi. Shunt B: 4.828e-006

BUS-0010 BUS-0009 1 13800.00 20.00 Miles
+ Seq Impedance: 3.21361 + J 6.88149 Per Unit; Equi. Shunt B: 0.000124558
0 Seq Impedance: 6.21928 + J 30.5929 Per Unit; Equi. Shunt B: 5.31299e-005

## TRANSFORMER INPUT DATA

```
RECORD           VOLTS   SECONDARY   VOLTS   FULL-LOAD   NOMINAL
PRIMARY          L-L     RECORD      L-L     KVA         KVA

BUS-0008      Y  13800.0  BUS-0005     YG  4160.00   500.00        500.00
Pos. Seq. Z%:   1.000 + J   4.90  2.00 + j   9.80 PU
Zero Seq. Z%:   1.000 + J   4.90  2.00 + j   9.80 PU
Taps  Pri.  1.01 %  Sec. 1.000 %  Phase Shift (Pri. Leading Sec.):  0.000 Deg.

BUS-0010      Y  13800.0  BUS-0006     YG  4160.00 4312.50         3750.00
Pos. Seq. Z%:   1.000 + J   6.93 0.266 + j   1.85 PU
Zero Seq. Z%:   1.000 + J   6.93 0.266 + j   1.85 PU
Taps  Pri. 1.000 %  Sec. 0.980 %  Phase Shift (Pri. Leading Sec.):  0.000 Deg.
```

## TRANSFORMER DATA (THREE WINDING)

```
Pri.   BUS-0012      13800    Pri-Sec     0 + J 25.602   100000
 0 Seq. Impedance:      0 + J 25.602 %  Pri. Neutral Z:      0 + J    0 Ohms
 Pri. Tap: 1 %     Sec. Tap: 1 %   Phase Shift of Pri. Leading Sec.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.2560 Per Unit
Sec.   BUS-0025        4160     Pri-Ter      0 + J    14    100000
 0 Seq. Impedance:      0 + J   14 %  Ter. Neutral Z:      0 + J    0 Ohms
 Pri. Tap: 1 %     Ter. Tap: 0 %   Phase Shift of Pri. Leading Ter.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.1400 Per Unit
Ter.      BUS-0004   4160      Sec-Ter      0 + J    10    100000
 0 Seq. Impedance:      0 + J   10 %  Sec. Neutral Z:      0 + J    0 Ohms
 Sec. Tap: 1 %     Ter. Tap: 0 %   Phase Shift of Sec. Leading Ter.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.1000 Per Unit

Pri.   BUS-0009      13800    Pri-Sec     0 + J  20.8    100000
 0 Seq. Impedance:      0 + J 20.8 %  Pri. Neutral Z:      0 + J    0 Ohms
 Pri. Tap: 1 %     Sec. Tap: 1 %   Phase Shift of Pri. Leading Sec.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.2080 Per Unit
Sec.   BUS-0026        4160     Pri-Ter      0 + J  20.8    100000
 0 Seq. Impedance:      0 + J 20.8 %  Ter. Neutral Z:      0 + J    0 Ohms
 Pri. Tap: 1 %     Ter. Tap: 0 %   Phase Shift of Pri. Leading Ter.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.2080 Per Unit
Ter.      BUS-0006   4160      Sec-Ter      0 + J    11    100000
 0 Seq. Impedance:      0 + J   11 %  Sec. Neutral Z:      0 + J    0 Ohms
 Sec. Tap: 1 %     Ter. Tap: 0 %   Phase Shift of Sec. Leading Ter.: 0.0 Deg.
 Equivalent Zero Seq. Impedance :    0.00000 + J   0.1100 Per Unit
```

## GENERATION DATA

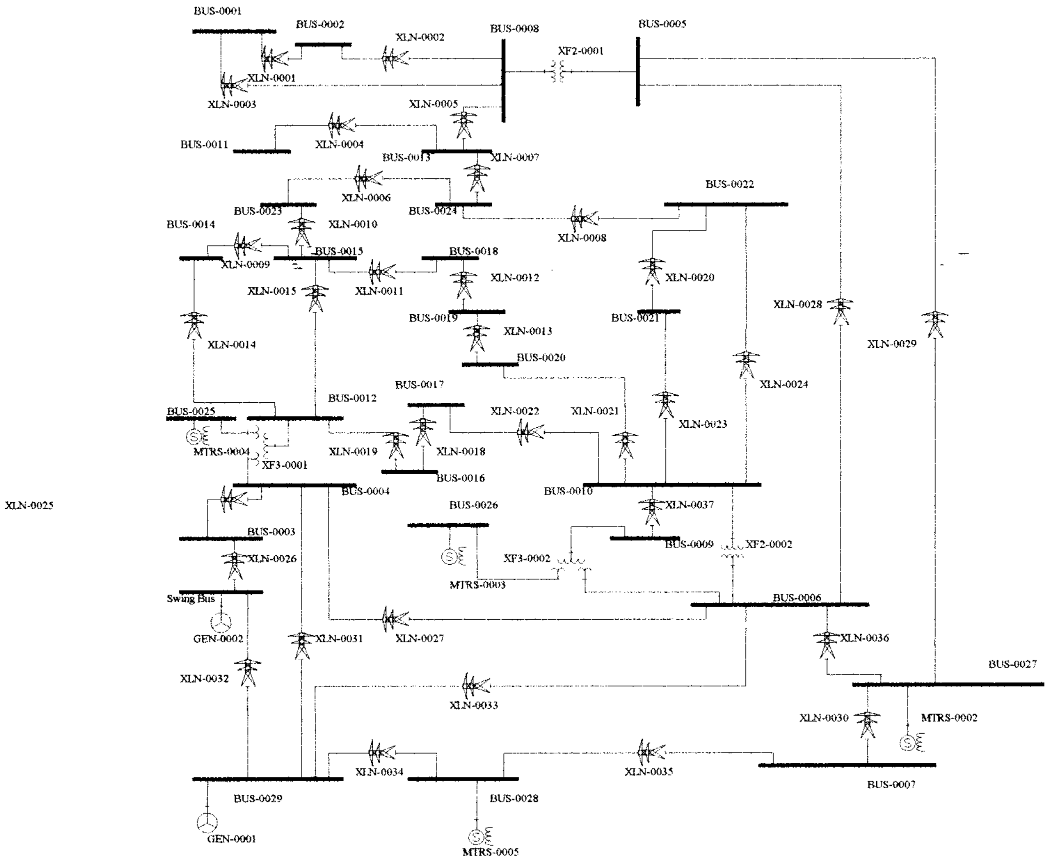
| BUS NAME | GENERATION | VOLT | SIZE | InitKW | MaxKVAR | TYPE |
|---|---|---|---|---|---|---|
| BUS-0029 | GEN-0001 | 1 pu | 500.00 kVA | 300.00 | 0.00000 | PQ |
| BUS-0030 | GEN-0002 | 1 pu | 500.00 kVA | 0.00000 | 0.00000 | SB |

## MOTOR LOAD DATA

| BUS NAME | LOAD NAME | VOLT | SIZE | # | TYPE | EFF | PF |
|---|---|---|---|---|---|---|---|
| BUS-0025 | MTRS-0004 | 4160 | 500.0 | 1 | HP KVA | 0.90 | 0.85 LAG |
| BUS-0026 | MTRS-0003 | 4160 | 500.0 | 1 | HP KVA | 0.90 | 0.86 LAG |
| BUS-0027 | MTRS-0002 | 4160 | 500.0 | 1 | HP KVA | 0.90 | 0.86 LAG |
| BUS-0028 | MTRS-0005 | 4160 | 500.0 | 1 | HP KVA | 0.92 | 0.86 LAG |

# APPENDIX F

## HI_WAVE Data Before Application of Filters



IEEE 30 TEST BUS SYSTEM

# HI_WAVE Report

**Date: 2 May 2002**
**Time: 2:15:48AM**

**Buses**

| Bus Name | Bus Voltage | THD% | RMS (V) | TIF |
|---|---|---|---|---|
| BUS-0001 | 13,800 | 5.25 | 26,804.78 | 59.31 |
| BUS-0002 | 13,800 | 5.25 | 26,804.78 | 59.31 |
| BUS-0003 | 4,160 | 4.38 | 6,891.53 | 244.43 |
| BUS-0004 | 4,160 | 4.60 | 7,537.06 | 100.97 |
| BUS-0005 | 4,160 | 8.26 | 8,132.30 | 39.50 |
| BUS-0006 | 4,160 | 7.34 | 7,755.62 | 64.73 |
| BUS-0007 | 4,160 | 16.71 | 8,693.05 | 127.29 |
| BUS-0008 | 13,800 | 4.89 | 26,753.96 | 34.08 |
| BUS-0009 | 13,800 | 3.16 | 25,921.31 | 60.54 |
| BUS-0010 | 13,800 | 3.20 | 25,780.40 | 56.18 |
| BUS-0011 | 13,800 | 4.90 | 26,516.01 | 117.80 |
| BUS-0012 | 13,800 | 3.11 | 25,257.43 | 100.52 |
| BUS-0013 | 13,800 | 4.55 | 26,488.90 | 68.48 |
| BUS-0014 | 13,800 | 3.03 | 25,446.83 | 107.20 |
| BUS-0015 | 13,800 | 2.73 | 25,591.58 | 52.44 |
| BUS-0016 | 13,800 | 4.00 | 25,482.18 | 182.40 |
| BUS-0017 | 13,800 | 3.82 | 25,654.76 | 159.96 |
| BUS-0018 | 13,800 | 3.77 | 25,712.48 | 146.41 |
| BUS-0019 | 13,800 | 4.32 | 25,786.61 | 180.94 |
| BUS-0020 | 13,800 | 3.59 | 25,803.56 | 109.86 |
| BUS-0021 | 13,800 | 3.47 | 25,891.57 | 67.75 |
| BUS-0022 | 13,800 | 3.43 | 25,955.77 | 41.22 |
| BUS-0023 | 13,800 | 3.35 | 25,882.85 | 98.04 |
| BUS-0024 | 13,800 | 3.82 | 26,130.96 | 85.87 |
| BUS-0025 | 4,160 | 4.61 | 7,609.90 | 100.67 |
| BUS-0026 | 4,160 | 7.34 | 7,830.63 | 64.87 |
| BUS-0027 | 4,160 | 10.83 | 8,867.64 | 135.72 |
| BUS-0028 | 4,160 | 15.42 | 8,610.96 | 118.63 |
| BUS-0029 | 4,160 | 3.04 | 7,301.12 | 59.49 |
| Swing Bus | 4,160 | 2.39 | 4,633.99 | 142.76 |

**Branches**

| Component Name | Type | From Bus<br>To Bus | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| XLN-0001 | XLine | BUS-0001<br>BUS-0002 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0002 | XLine | BUS-0002<br>BUS-0008 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0003 | XLine | BUS-0001<br>BUS-0008 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XF2-0001 | Xformer2 | BUS-0008<br>BUS-0005 | 13,800 | 23.49 | 6 | 1,291.36 | 3.64 | 6 | -29 |
| XLN-0004 | XLine | BUS-0011<br>BUS-0013 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0005 | XLine | BUS-0008<br>BUS-0013 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0006 | XLine | BUS-0023<br>BUS-0024 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0007 | XLine | BUS-0013<br>BUS-0024 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0008 | XLine | BUS-0024<br>BUS-0022 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0009 | XLine | BUS-0014<br>BUS-0015 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0010 | XLine | BUS-0023<br>BUS-0015 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0011 | XLine | BUS-0015<br>BUS-0018 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0012 | XLine | BUS-0018<br>BUS-0019 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0013 | XLine | BUS-0019<br>BUS-0020 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0014 | XLine | BUS-0014<br>BUS-0012 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0015 | XLine | BUS-0015<br>BUS-0012 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0018 | XLine | BUS-0017<br>BUS-0016 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0019 | XLine | BUS-0012<br>BUS-0016 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0020 | XLine | BUS-0022<br>BUS-0021 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0021 | XLine | BUS-0020<br>BUS-0010 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |

**Branches**

| Component Name | Type | From Bus<br>To Bus | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| XLN-0022 | XLine | BUS-0017<br>BUS-0010 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0023 | XLine | BUS-0021<br>BUS-0010 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0024 | XLine | BUS-0022<br>BUS-0010 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0025 | XLine | BUS-0003<br>BUS-0004 | 4,160 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0026 | XLine | BUS-0003<br>Swing Bus | 4,160 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0027 | XLine | BUS-0004<br>BUS-0006 | 4,160 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0028 | XLine | BUS-0005<br>BUS-0006 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0029 | XLine | BUS-0005<br>BUS-0027 | 4,160 | 0.00 | 5 | 0.00 | 0.00 | 0 | 0 |
| XLN-0030 | XLine | BUS-0027<br>BUS-0007 | 4,160 | 0.00 | 4 | 0.00 | 0.00 | 0 | 0 |
| XLN-0031 | XLine | BUS-0004<br>BUS-0029 | 4,160 | 0.00 | 3 | 0.00 | 0.00 | 0 | 0 |
| XLN-0032 | XLine | Swing Bus<br>BUS-0029 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0033 | XLine | BUS-0029<br>BUS-0006 | 4,160 | 0.00 | 3 | 0.00 | 0.00 | 0 | 0 |
| XLN-0034 | XLine | BUS-0029<br>BUS-0028 | 4,160 | 0.00 | 7 | 0.00 | 0.00 | 0 | 0 |
| XLN-0035 | XLine | BUS-0028<br>BUS-0007 | 4,160 | 0.00 | 4 | 0.00 | 0.00 | 0 | 0 |
| XLN-0036 | XLine | BUS-0006<br>BUS-0027 | 4,160 | 0.00 | 5 | 0.00 | 0.00 | 0 | 0 |
| XF2-0002 | Xformer2 | BUS-0010<br>BUS-0006 | 13,800 | 10.61 | 17 | 1,527.09 | 1.42 | 17 | -165 |
| XF3-0001 | Xformer3 | BUS-0012<br>BUS-0025 | 13,800 | 0.00 | 5 | 0.00 | 0.00 | 0 | 0 |
| XLN-0037 | XLine | BUS-0010<br>BUS-0009 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XF3-0002 | Xformer3 | BUS-0009<br>BUS-0026 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |

| ULTILITY, GENERATOR AND MOTOR DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| Component Name | Component Type | Bus Name | Bus Voltage | Base Voltage | Base KVA | R1<br>R2<br>R0 | X1<br>X2<br>X0 |
| GEN-0001 | SYNCH GENERATOR | BUS-0029 | 4160 | 4160 | 500 | 1.5000<br>1.5000<br>1.5000 | 30.0000<br>30.0000<br>30.0000 |
| GEN-0002 | SYNCH GENERATOR | Swing Bus | 4160 | 4160 | 500 | 1.5000<br>1.5000<br>1.5000 | 30.0000<br>30.0000<br>30.0000 |

**Motors**

| Motor Name | Type | Bus Name | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| MTRS-0002 | Syn Mtr | BUS-0027 | 4,160 | 21.46 | 32 | 6,441.92 | 2.80 | 32 | -131 |
| MTRS-0003 | Syn Mtr | BUS-0026 | 4,160 | 7.27 | 36 | 803.37 | 1.07 | 36 | -126 |
| MTRS-0004 | Syn Mtr | BUS-0025 | 4,160 | 51.44 | 42 | 19,073.89 | 9.47 | 37 | -126 |
| MTRS-0005 | Syn Mtr | BUS-0028 | 4,160 | 6.28 | 32 | 5,182.63 | 1.50 | 32 | -130 |

| VOLTAGE DISTORTION SUMMARY | | | | | |
|---|---|---|---|---|---|
| Bus Name | Voltage | V_RMS(V) | V_TIF | V_THD(%) | IEEE-519 |
| BUS-0001 | 13800 | 26804.78 | 59.3107 | 5.2523> | 5.0 |
| BUS-0002 | 13800 | 26804.78 | 59.3107 | 5.2523> | 5.0 |
| BUS-0005 | 4160 | 8132.30 | 39.5023 | 8.2576> | 5.0 |
| BUS-0006 | 4160 | 7755.62 | 64.7295 | 7.3378> | 5.0 |
| BUS-0007 | 4160 | 8693.05 | 127.2905 | 16.7125> | 5.0 |
| BUS-0026 | 4160 | 7830.63 | 64.8666 | 7.3427> | 5.0 |
| BUS-0027 | 4160 | 8867.64 | 135.7219 | 10.8281> | 5.0 |
| BUS-0028 | 4160 | 8610.96 | 118.6316 | 15.4249> | 5.0 |

## HARMONIC CURRENT SPECTRUM REPORT

Device Name: XLN-0026
From: BUS-0003 (4160V)
To: Swing Bus (4160V)
Connected to a utility as a PCC. (Isc/Ilf = 665.096)

| Harmonic Order | Harmonic Amperes | Phase Angle | Distortion Percent | IEEE-519 Limit |
|---|---|---|---|---|
| 1 | 0.000 | 0.00 | | |
| 2 | 0.000 | 162.40 | 0.000 | 3.000 |
| 3 | 0.000 | 143.74 | 0.000 | 12.000 |
| 4 | 0.000 | -138.82 | 0.000 | 3.000 |
| 5 | 0.000 | 59.17 | 0.000 | 12.000 |
| 6 | 0.000 | 137.74 | 0.000 | 3.000 |
| 7 | 0.000 | 173.75 | 0.000 | 12.000 |
| 8 | 0.000 | 162.58 | 0.000 | 3.000 |
| 9 | 0.000 | 115.74 | 0.000 | 12.000 |
| 10 | 0.000 | -179.73 | 0.000 | 3.000 |
| 11 | 0.000 | -116.84 | 0.000 | 5.500 |
| 13 | 0.000 | 81.74 | 0.000 | 5.500 |
| 17 | 0.000 | 17.20 | 0.000 | 5.000 |
| 19 | 0.000 | 113.98 | 0.000 | 5.000 |
| 23 | 0.000 | 62.00 | 0.000 | 2.000 |
| 25 | 0.000 | 53.60 | 0.000 | 2.000 |
| 29 | 0.000 | 42.74 | 0.000 | 2.000 |
| 31 | 0.000 | 175.69 | 0.000 | 2.000 |

Voltage: 4160.0 I_RMS: 1.51 I_THD(%): 0.00
I_K: 0.00 IEEE-519 LIMIT (THD%): 15.0

## Harmonic Sources

| Source Name<br>Bus Connected To | Lib. Source Name<br>Component Type | Bus Voltage<br>Rated kVA | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|
| **MTRS-0002**<br>BUS-0027 | IEEE 6 Pulse<br>Syn Mtr | 4,160<br>481.91 | 21.46 | 32 | 6,441.92 | 2.80 | 32 | -131 |
| **MTRS-0003**<br>BUS-0026 | ARC Furnace<br>Syn Mtr | 4,160<br>481.91 | 7.27 | 36 | 803.37 | 1.07 | 36 | -126 |
| **MTRS-0004**<br>BUS-0025 | Typical 6 Pulse IGBT<br>Syn Mtr | 4,160<br>487.58 | 51.44 | 42 | 19,073.89 | 9.47 | 37 | -126 |
| **MTRS-0005**<br>BUS-0028 | Typical 12 Pulse<br>Syn Mtr | 4,160<br>471.44 | 6.28 | 32 | 5,182.63 | 1.50 | 32 | -130 |

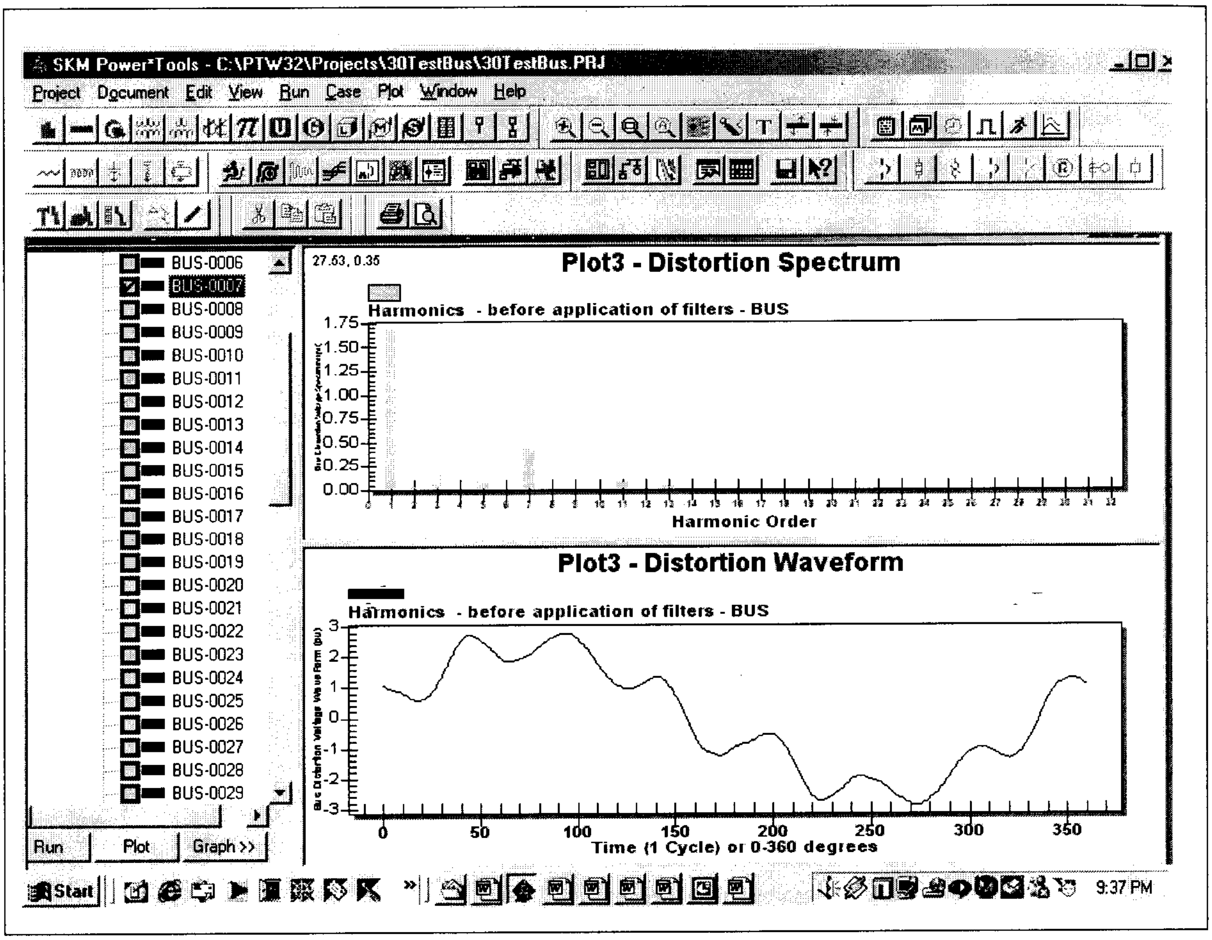


Figure F-1. Distortion waveform and spectrum at bus-0007 before application of filters.

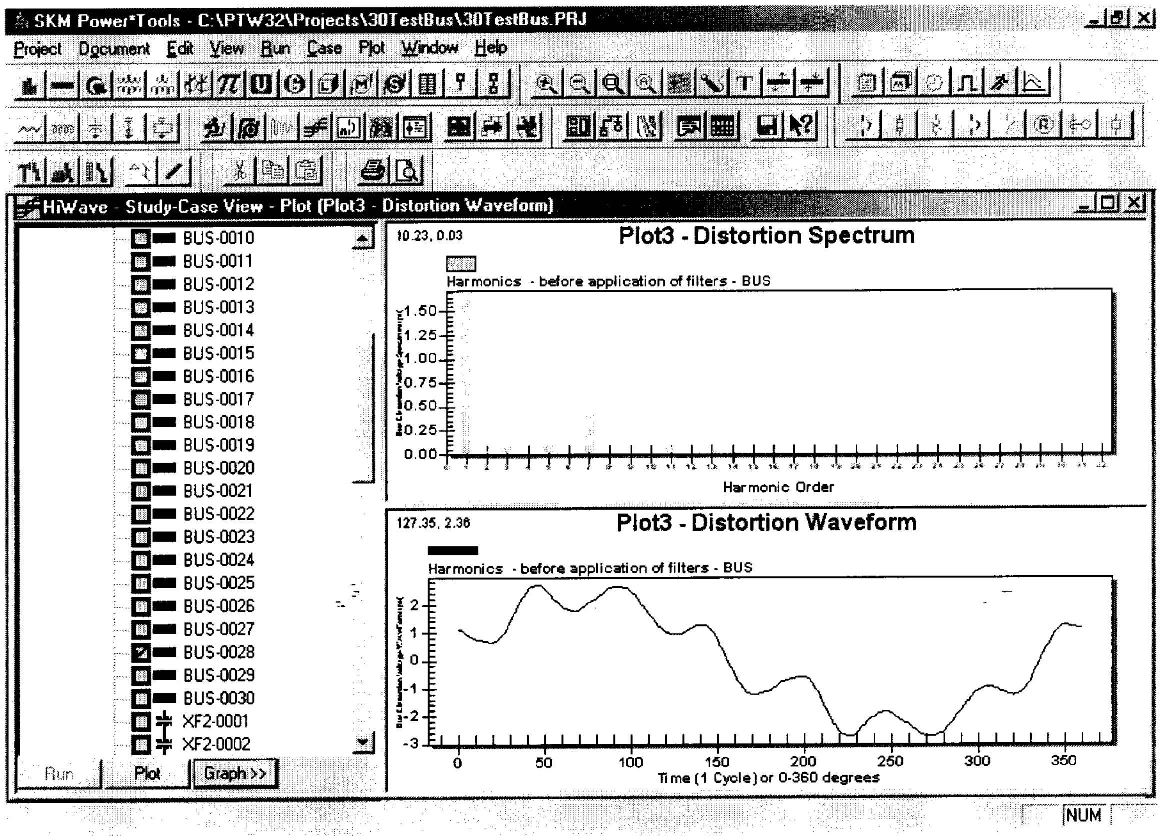


Figure F-2. Distortion waveform and spectrum at bus-0028 before application of filters.

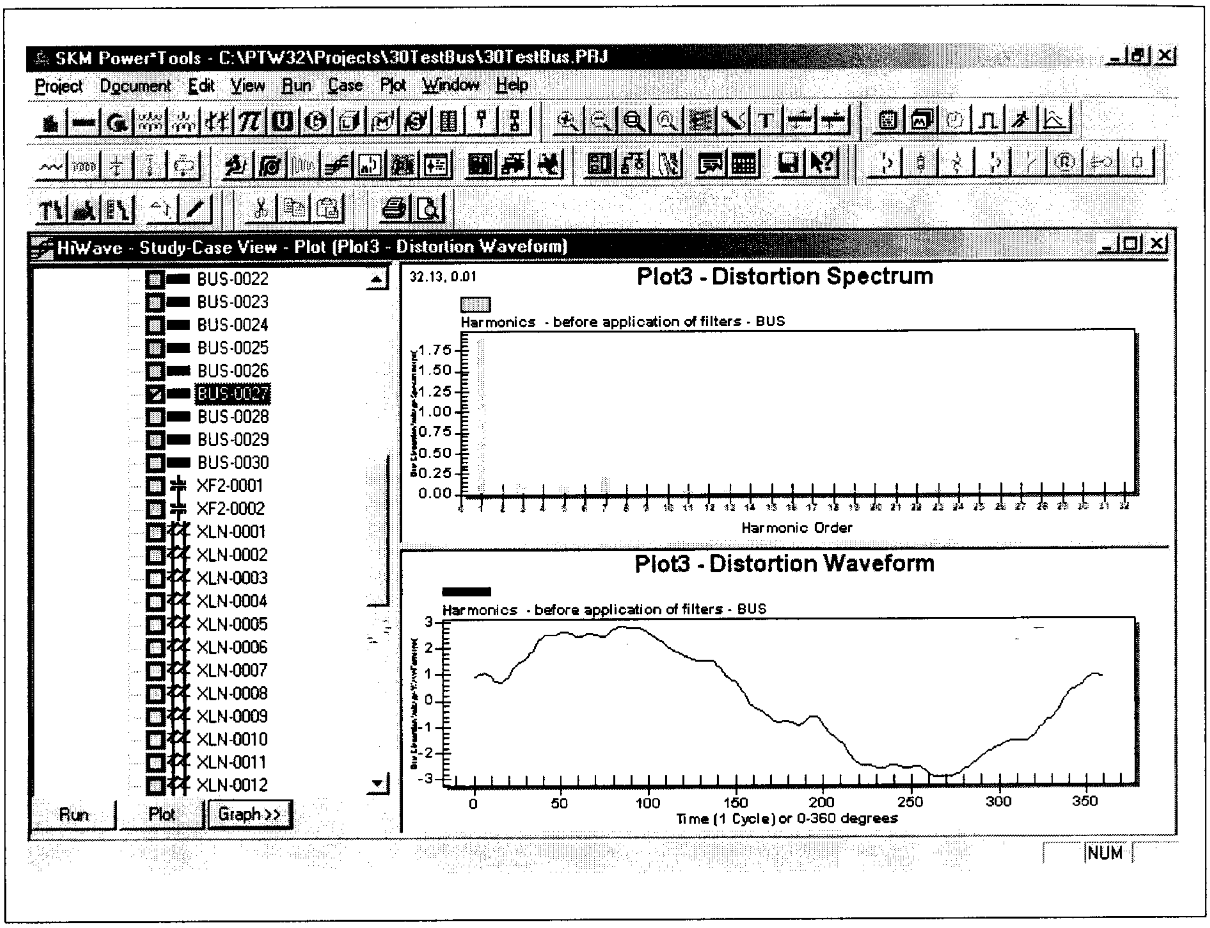
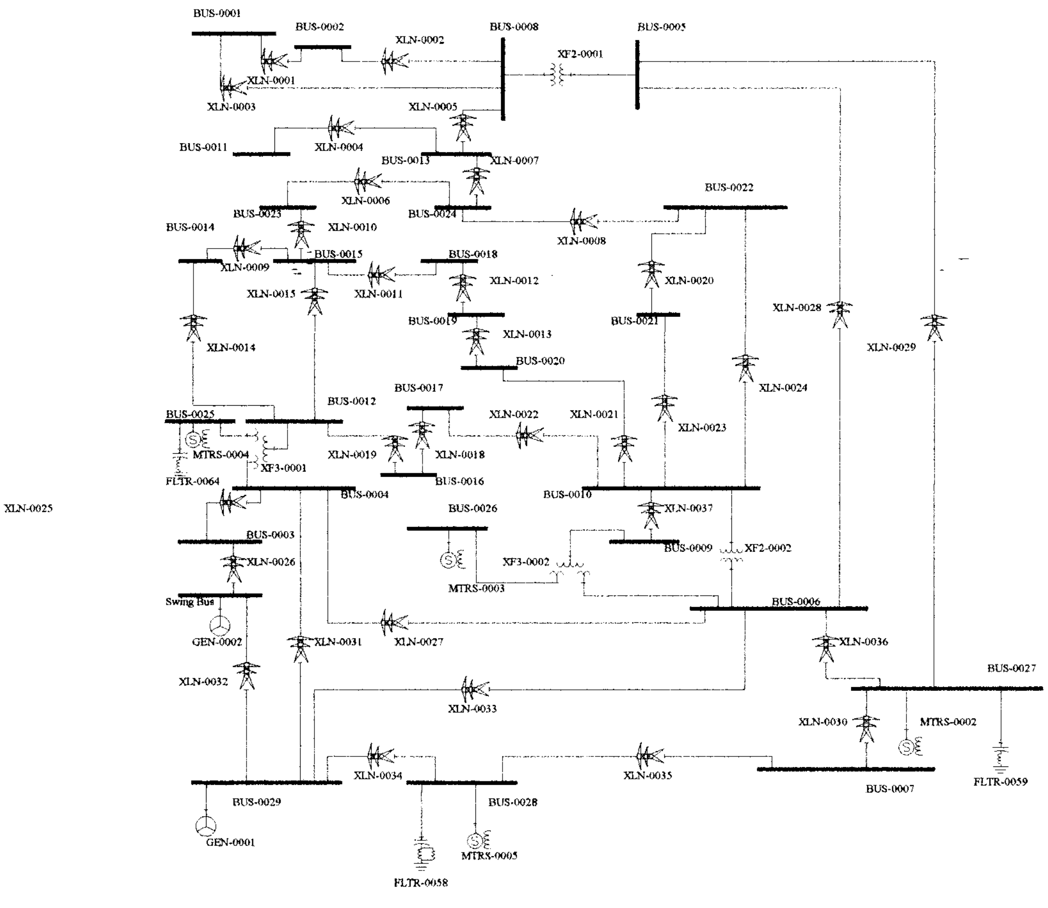


Figure F-3. Distortion waveform and spectrum at bus-0027 before application of filters.

# APPENDIX G

## HI_WAVE Data After Application of Filters



**IEEE 30 TEST BUS SYSTEM**

# HI_WAVE Report

**Date: 2 May 2002**
**Time: 12:49:17AM**

**Buses**

| Bus Name | Bus Voltage | THD% | RMS (V) | TIF |
|---|---|---|---|---|
| BUS-0001 | 13,800 | 2.01 | 26,773.31 | 32.29 |
| BUS-0002 | 13,800 | 2.01 | 26,773.31 | 32.29 |
| BUS-0003 | 4,160 | 3.65 | 6,889.53 | 264.63 |
| BUS-0004 | 4,160 | 1.14 | 7,529.61 | 60.10 |
| BUS-0005 | 4,160 | 1.73 | 8,105.93 | 19.65 |
| BUS-0006 | 4,160 | 2.31 | 7,736.88 | 53.18 |
| BUS-0007 | 4,160 | 0.56 | 8,574.27 | 21.72 |
| BUS-0008 | 13,800 | 1.80 | 26,726.31 | 18.61 |
| BUS-0009 | 13,800 | 1.19 | 25,910.19 | 52.39 |
| BUS-0010 | 13,800 | 1.15 | 25,768.95 | 46.53 |
| BUS-0011 | 13,800 | 2.24 | 26,490.84 | 114.82 |
| BUS-0012 | 13,800 | 1.14 | 25,246.84 | 60.68 |
| BUS-0013 | 13,800 | 1.61 | 26,464.93 | 43.02 |
| BUS-0014 | 13,800 | 1.86 | 25,439.54 | 126.24 |
| BUS-0015 | 13,800 | 1.01 | 25,583.33 | 53.59 |
| BUS-0016 | 13,800 | 1.88 | 25,466.36 | 114.70 |
| BUS-0017 | 13,800 | 1.85 | 25,640.44 | 111.24 |
| BUS-0018 | 13,800 | 1.75 | 25,698.12 | 90.21 |
| BUS-0019 | 13,800 | 2.01 | 25,767.77 | 105.86 |
| BUS-0020 | 13,800 | 1.33 | 25,789.25 | 58.88 |
| BUS-0021 | 13,800 | 1.49 | 25,878.91 | 73.73 |
| BUS-0022 | 13,800 | 1.12 | 25,942.16 | 32.08 |
| BUS-0023 | 13,800 | 1.76 | 25,872.35 | 115.49 |
| BUS-0024 | 13,800 | 1.63 | 26,115.37 | 92.58 |
| BUS-0025 | 4,160 | 1.15 | 7,602.34 | 59.50 |
| BUS-0026 | 4,160 | 2.31 | 7,811.69 | 53.36 |
| BUS-0027 | 4,160 | 0.61 | 8,816.27 | 21.62 |
| BUS-0028 | 4,160 | 0.47 | 8,510.41 | 5.23 |
| BUS-0029 | 4,160 | 0.72 | 7,297.93 | 49.54 |
| Swing Bus | 4,160 | 2.09 | 4,633.68 | 152.68 |

**Branches**

| Component Name | Type | From Bus<br>To Bus | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| XLN-0001 | XLine | BUS-0001<br>BUS-0002 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0002 | XLine | BUS-0002<br>BUS-0008 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0003 | XLine | BUS-0001<br>BUS-0008 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XF2-0001 | Xformer2 | BUS-0008<br>BUS-0005 | 13,800 | 7.03 | 6 | 482.06 | 1.27 | 6 | -29 |
| XLN-0004 | XLine | BUS-0011<br>BUS-0013 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0005 | XLine | BUS-0008<br>BUS-0013 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0006 | XLine | BUS-0023<br>BUS-0024 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0007 | XLine | BUS-0013<br>BUS-0024 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0008 | XLine | BUS-0024<br>BUS-0022 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0009 | XLine | BUS-0014<br>BUS-0015 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0010 | XLine | BUS-0023<br>BUS-0015 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0011 | XLine | BUS-0015<br>BUS-0018 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0012 | XLine | BUS-0018<br>BUS-0019 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0013 | XLine | BUS-0019<br>BUS-0020 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0014 | XLine | BUS-0014<br>BUS-0012 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0015 | XLine | BUS-0015<br>BUS-0012 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0018 | XLine | BUS-0017<br>BUS-0016 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0019 | XLine | BUS-0012<br>BUS-0016 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0020 | XLine | BUS-0022<br>BUS-0021 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0021 | XLine | BUS-0020<br>BUS-0010 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |

**Branches**

| Component Name | Type | From Bus<br>To Bus | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| XLN-0022 | XLine | BUS-0017<br>BUS-0010 | 13,800 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0023 | XLine | BUS-0021<br>BUS-0010 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0024 | XLine | BUS-0022<br>BUS-0010 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0025 | XLine | BUS-0003<br>BUS-0004 | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0026 | XLine | BUS-0003<br>Swing Bus | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0027 | XLine | BUS-0004<br>BUS-0006 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0028 | XLine | BUS-0005<br>BUS-0006 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0029 | XLine | BUS-0005<br>BUS-0027 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0030 | XLine | BUS-0027<br>BUS-0007 | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0031 | XLine | BUS-0004<br>BUS-0029 | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0032 | XLine | Swing Bus<br>BUS-0029 | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0033 | XLine | BUS-0029<br>BUS-0006 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0034 | XLine | BUS-0029<br>BUS-0028 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XLN-0035 | XLine | BUS-0028<br>BUS-0007 | 4,160 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XLN-0036 | XLine | BUS-0006<br>BUS-0027 | 4,160 | 0.00 | 1 | 0.00 | 0.00 | 0 | 0 |
| XF2-0002 | Xformer2 | BUS-0010<br>BUS-0006 | 13,800 | 2.04 | 17 | 1,099.54 | 1.07 | 17 | -165 |
| XF3-0001 | Xformer3 | BUS-0012<br>BUS-0025 | 13,800 | 0.00 | 2 | 0.00 | 0.00 | 0 | 0 |
| XLN-0037 | XLine | BUS-0010<br>BUS-0009 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |
| XF3-0002 | Xformer3 | BUS-0009<br>BUS-0026 | 13,800 | 0.00 | 0 | 0.00 | 0.00 | 0 | 0 |

| PASSIVE FILTER DATA | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Filter Name | Bus Name | Bus Voltage | Rated Voltage | Connect | Filter Type | Capacitor KVAR | Tuned Order | Q | M | R (Ω) | L (H) | C (μF) |
| FLTR-0058 | BUS-0028 | 4160 | 4160 | WYE_G | HighPass | 350.0 | 11 | | 3 | 4.4950<br>4.4950 | 0.0033<br>0.0033 | 53.6476<br>53.6476 |
| FLTR-0059 | BUS-0027 | 4160 | 4160 | WYE_G | SingleTuned | 500.0 | 5 | 30 | | 0.2307<br>0.2307 | 0.0037<br>0.0037 | 76.6394<br>76.6394 |
| FLTR-0064 | BUS-0025 | 4160 | 4160 | WYE_G | SingleTuned | 500.0 | 5 | 30 | | 0.2307<br>0.2307 | 0.0037<br>0.0037 | 76.6394<br>76.6394 |

**Filters**

| Filter Name | Bus Name | Bus Voltage | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|
| FLTR-0058 | BUS-0028 | 4,160 | 2.28 | 102 | 5,121.05 | 1.05 | 102 | -10 |
| FLTR-0059 | BUS-0027 | 4,160 | 4.38 | 153 | 5,731.67 | 1.07 | 153 | -11 |
| FLTR-0064 | BUS-0025 | 4,160 | 0.00 | 14 | 0.00 | 0.00 | 0 | 0 |

**Motors**

| Motor Name | Type | Bus Name | Bus Volt. | THD% | RMS(A) | I T | K | LF Amps | LF Angle |
|---|---|---|---|---|---|---|---|---|---|
| MTRS-0002 | Syn Mtr | BUS-0027 | 4,160 | 21.46 | 32 | 6,441.92 | 2.80 | 32 | -131 |
| MTRS-0003 | Syn Mtr | BUS-0026 | 4,160 | 7.27 | 36 | 803.37 | 1.07 | 36 | -126 |
| MTRS-0004 | Syn Mtr | BUS-0025 | 4,160 | 51.44 | 42 | 19,073.89 | 9.47 | 37 | -126 |
| MTRS-0005 | Syn Mtr | BUS-0028 | 4,160 | 6.28 | 32 | 5,182.63 | 1.50 | 32 | -130 |

# FILTER SPECTRUM REPORT

Filter Name: FLTR-0058    (HighPass)
Bus Name: BUS-0028 (4160V)

| Harmonic Order | IR (Amp) | IL (Amp) | IC (Amp) | R (kW) | L (kVAR) | C (kVAR) | R (V) | L (V) | C (V) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 26.76533 | 98.13339 | 101.71797 | | 35.41902 | 1534.74156 | 208.38136 | 208.38136 | 8711.17462 |
| 2 | 0.40093 | 0.73499 | 0.83723 | | 0.00397 | 0.05199 | 3.12143 | 3.12143 | 35.85038 |
| 3 | 0.00445 | 0.00544 | 0.00702 | | | | 0.03463 | 0.03463 | 0.20049 |
| 4 | 0.00420 | 0.00385 | 0.00569 | | | | 0.03268 | 0.03268 | 0.12191 |
| 5 | 0.80087 | 0.58727 | 0.99312 | | 0.00634 | 0.02926 | 6.23518 | 6.23518 | 17.01018 |
| 6 | 0.00743 | 0.00454 | 0.00871 | | | | 0.05786 | 0.05786 | 0.12432 |
| 7 | 0.56484 | 0.29585 | 0.63763 | | 0.00225 | 0.00862 | 4.39755 | 4.39755 | 7.80096 |
| 8 | 0.00167 | 0.00077 | 0.00184 | | | | 0.01300 | 0.01300 | 0.01966 |
| 9 | 0.00499 | 0.00203 | 0.00539 | | | | 0.03884 | 0.03884 | 0.05126 |
| 10 | 0.00553 | 0.00203 | 0.00589 | | | | 0.04306 | 0.04306 | 0.05045 |
| 11 | 1.42576 | 0.47522 | 1.50288 | | 0.00914 | 0.03046 | 11.10026 | 11.10026 | 11.70063 |
| 13 | 0.92991 | 0.26226 | 0.96618 | | 0.00329 | 0.01065 | 7.23978 | 7.23978 | 6.36494 |
| 17 | 0.15791 | 0.03406 | 0.16154 | | 0.00007 | 0.00023 | 1.22941 | 1.22941 | 0.81379 |
| 19 | 0.15111 | 0.02916 | 0.15390 | | 0.00006 | 0.00018 | 1.17648 | 1.17648 | 0.69369 |
| 23 | 0.10193 | 0.01625 | 0.10322 | | 0.00002 | 0.00007 | 0.79358 | 0.79358 | 0.38433 |
| 25 | 0.20160 | 0.02957 | 0.20375 | | 0.00008 | 0.00025 | 1.56953 | 1.56953 | 0.69798 |
| 29 | 0.06034 | 0.00763 | 0.06082 | | 0.00001 | 0.00002 | 0.46980 | 0.46980 | 0.17962 |
| 31 | 0.01443 | 0.00171 | 0.01453 | | | | 0.11237 | 0.11237 | 0.04015 |

Capacitor Rated Voltage: 4160.00    Rated 3 Phase KVA: 350.00
V_RMS: 8711.279    V_CREST: 8793.279    I_RMS: 101.744    KVA: 1534.873
V_RMS: 209.4057% >    V_CREST: 211.3769% >    I_RMS: 209.4578% >    KVA: 438.5352% >
Limit: 110.0%    Limit: 169.7%    Limit: 180.0%    Limit: 135.0%

# FILTER SPECTRUM REPORT

Filter Name: FLTR-0059 (SingleTuned)
Bus Name: BUS-0027 (4160V)

| Harmonic Order | IR (Amp) | IL (Amp) | IC (Amp) | R (kW) | L (kVAR) | C (kVAR) | R (V) | L (V) | C (V) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 153.18500 | 153.18500 | 153.18500 | 16.24346 | 97.45127 | 2436.52220 | 61.22114 | 367.29111 | 9183.18419 |
| 2 | 0.92075 | 0.92075 | 0.92075 | 0.00059 | 0.00704 | 0.04401 | 0.36798 | 4.41537 | 27.59879 |
| 3 | 0.73535 | 0.73535 | 0.73535 | 0.00037 | 0.00674 | 0.01872 | 0.29388 | 5.28941 | 14.69424 |
| 4 | 0.07529 | 0.07529 | 0.07529 |  | 0.00009 | 0.00015 | 0.03009 | 0.72206 | 1.12833 |
| 5 | 5.99015 | 5.99015 | 5.99015 | 0.02484 | 0.74508 | 0.74515 | 2.39399 | 71.81280 | 71.81989 |
| 6 | 0.13317 | 0.13317 | 0.13317 | 0.00001 | 0.00044 | 0.00031 | 0.05322 | 1.91585 | 1.33059 |
| 7 | 2.28658 | 2.28658 | 2.28658 | 0.00362 | 0.15199 | 0.07756 | 0.91384 | 38.37764 | 19.58236 |
| 8 | 0.02126 | 0.02126 | 0.02126 |  | 0.00002 | 0.00001 | 0.00850 | 0.40780 | 0.15931 |
| 9 | 0.13226 | 0.13226 | 0.13226 | 0.00001 | 0.00065 | 0.00020 | 0.05286 | 2.85409 | 0.88098 |
| 10 | 0.00874 | 0.00874 | 0.00874 |  |  |  | 0.00349 | 0.20945 | 0.05237 |
| 11 | 1.19397 | 1.19397 | 1.19397 | 0.00099 | 0.06512 | 0.01346 | 0.47718 | 31.49052 | 6.50695 |
| 13 | 0.82303 | 0.82303 | 0.82303 | 0.00047 | 0.03657 | 0.00541 | 0.32893 | 25.65395 | 3.79534 |
| 17 | 0.49722 | 0.49722 | 0.49722 | 0.00017 | 0.01745 | 0.00151 | 0.19872 | 20.26721 | 1.75339 |
| 19 | 0.33298 | 0.33298 | 0.33298 | 0.00008 | 0.00875 | 0.00061 | 0.13308 | 15.16936 | 1.05061 |
| 23 | 0.20541 | 0.20541 | 0.20541 | 0.00003 | 0.00403 | 0.00019 | 0.08209 | 11.32777 | 0.53539 |
| 25 | 0.20796 | 0.20796 | 0.20796 | 0.00003 | 0.00449 | 0.00018 | 0.08311 | 12.46585 | 0.49868 |
| 29 | 0.07055 | 0.07055 | 0.07055 |  | 0.00060 | 0.00002 | 0.02819 | 4.90531 | 0.14583 |
| 31 | 0.00782 | 0.00782 | 0.00782 |  | 0.00001 |  | 0.00313 | 0.58159 | 0.01513 |

Capacitor Rated Voltage: 4160.00 Rated 3 Phase KVA: 500.00
V_RMS: 9183.543 V_CREST: 9334.732 I_RMS: 153.332 KVA: 2437.430
V_RMS: 220.7582% > V_CREST: 224.3926% > I_RMS: 220.9616% > KVA: 487.4859% >
Limit: 110.0% Limit: 169.7% Limit: 180.0% Limit: 135.0%

## FILTER SPECTRUM REPORT

Filter Name: FLTR-0064 (SingleTuned)
Bus Name: BUS-0025 (4160V)

| Harmonic Order | IR (Amp) | IL (Amp) | IC (Amp) | R (kW) | L (kVAR) | C (kVAR) | R (V) | L (V) | C (V) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | |
| 2 | 0.54442 | 0.54442 | 0.54442 | 0.00021 | 0.00246 | 0.01539 | 0.21758 | 2.61069 | 16.31839 |
| 3 | 0.52913 | 0.52913 | 0.52913 | 0.00019 | 0.00349 | 0.00969 | 0.21147 | 3.80606 | 10.57342 |
| 4 | 0.67289 | 0.67289 | 0.67289 | 0.00031 | 0.00752 | 0.01175 | 0.26892 | 6.45356 | 10.08469 |
| 5 | 13.46905 | 13.46905 | 13.46905 | 0.12558 | 3.76703 | 3.76740 | 5.38297 | 161.47343 | 161.48937 |
| 6 | 0.09158 | 0.09158 | 0.09158 | 0.00001 | 0.00021 | 0.00015 | 0.03660 | 1.31742 | 0.91496 |
| 7 | 4.21222 | 4.21222 | 4.21222 | 0.01228 | 0.51579 | 0.26319 | 1.68344 | 70.69742 | 36.07368 |
| 8 | 0.03437 | 0.03437 | 0.03437 | | 0.00004 | 0.00002 | 0.01374 | 0.65926 | 0.25755 |
| 9 | 0.09132 | 0.09132 | 0.09132 | 0.00001 | 0.00031 | 0.00010 | 0.03650 | 1.97070 | 0.60830 |
| 10 | 0.24289 | 0.24289 | 0.24289 | 0.00004 | 0.00245 | 0.00061 | 0.09707 | 5.82365 | 1.45606 |
| 11 | 0.55508 | 0.55508 | 0.55508 | 0.00021 | 0.01408 | 0.00291 | 0.22184 | 14.64012 | 3.02512 |
| 13 | 1.10226 | 1.10226 | 1.10226 | 0.00084 | 0.06559 | 0.00970 | 0.44052 | 34.35755 | 5.08298 |
| 17 | 0.22157 | 0.22157 | 0.22157 | 0.00003 | 0.00347 | 0.00030 | 0.08855 | 9.03155 | 0.78135 |
| 19 | 1.40455 | 1.40455 | 1.40455 | 0.00137 | 0.15566 | 0.01078 | 0.56134 | 63.98598 | 4.43160 |
| 23 | 0.03470 | 0.03470 | 0.03470 | | 0.00012 | 0.00001 | 0.01387 | 1.91364 | 0.09045 |
| 25 | 0.05493 | 0.05493 | 0.05493 | | 0.00031 | 0.00001 | 0.02195 | 3.29263 | 0.13172 |
| 29 | 0.56476 | 0.56476 | 0.56476 | 0.00022 | 0.03841 | 0.00114 | 0.22571 | 39.26966 | 1.16747 |
| 31 | 0.05860 | 0.05860 | 0.05860 | | 0.00044 | 0.00001 | 0.02342 | 4.35588 | 0.11333 |

Capacitor Rated Voltage: 4160.00 Rated 3 Phase KVA: 500.00
V_RMS: 167.093 V_CREST: 252.600 I_RMS: 14.288 KVA: 4.093
V_RMS: 4.0166% V_CREST: 6.0721% I_RMS: 20.5894% KVA: 0.8186%
Limit: 110.0% Limit: 169.7% Limit: 180.0% Limit: 135.0%

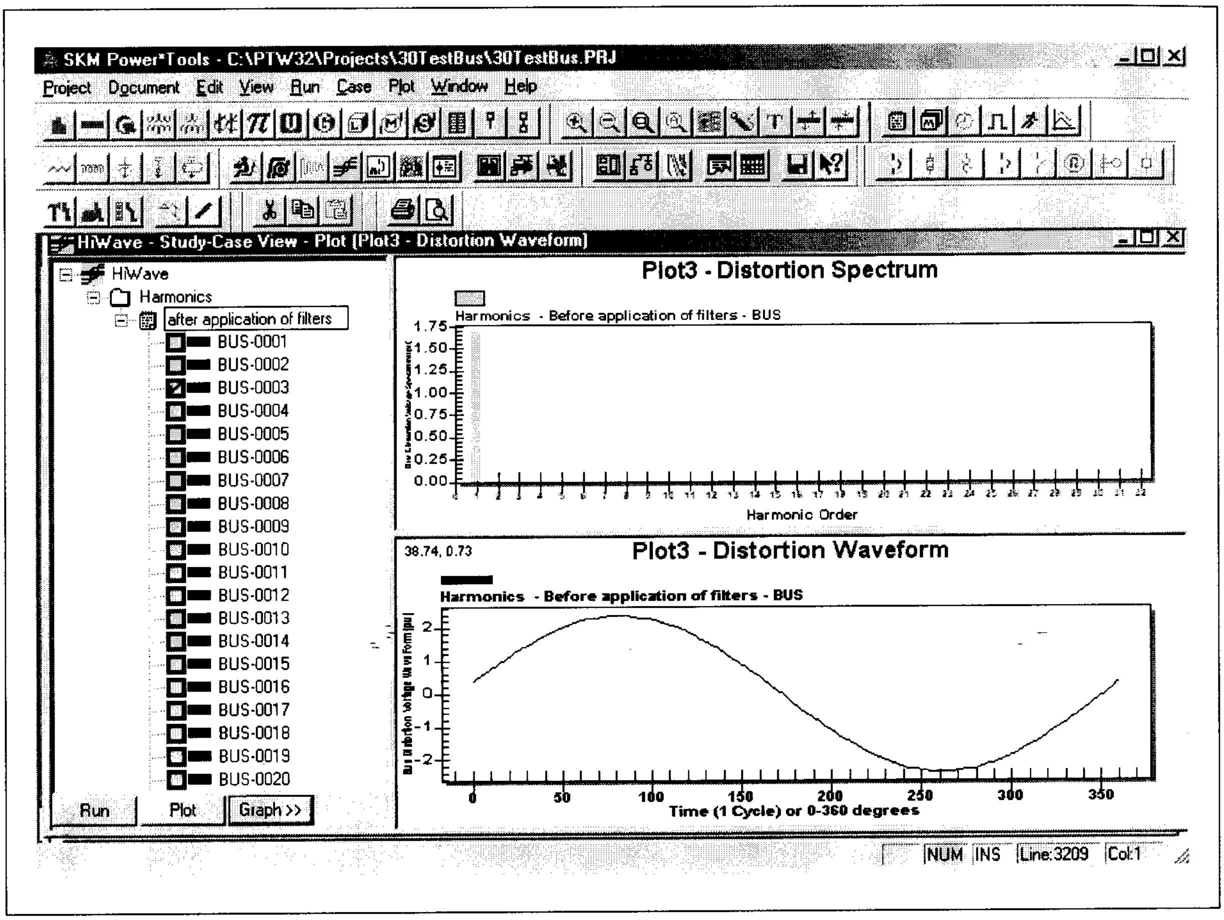


Figure G-1. Distortion waveform and spectrum at bus-0003 after application of filters.

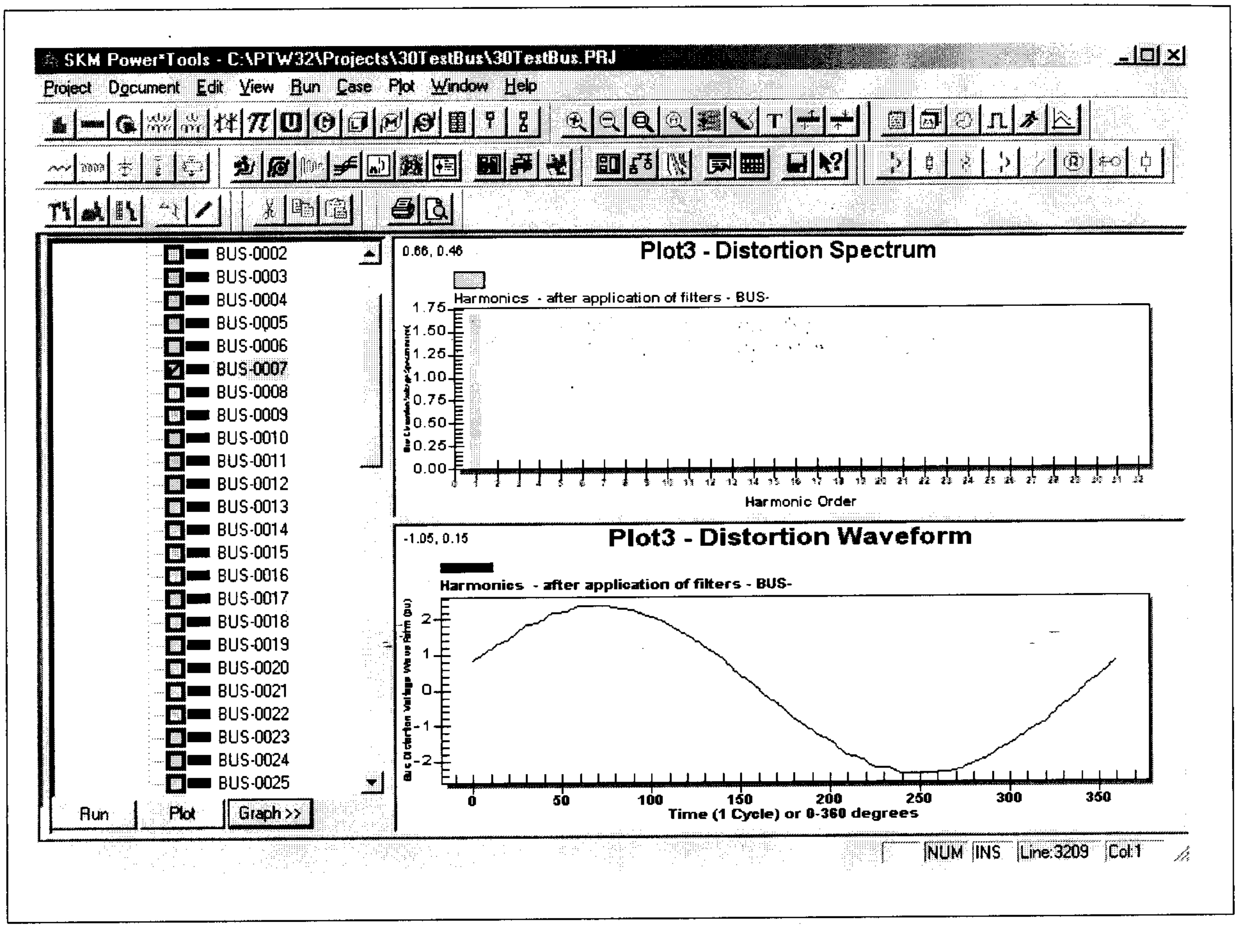


Figure G-2. Distortion waveform and spectrum at bus-0007 after application of filters.

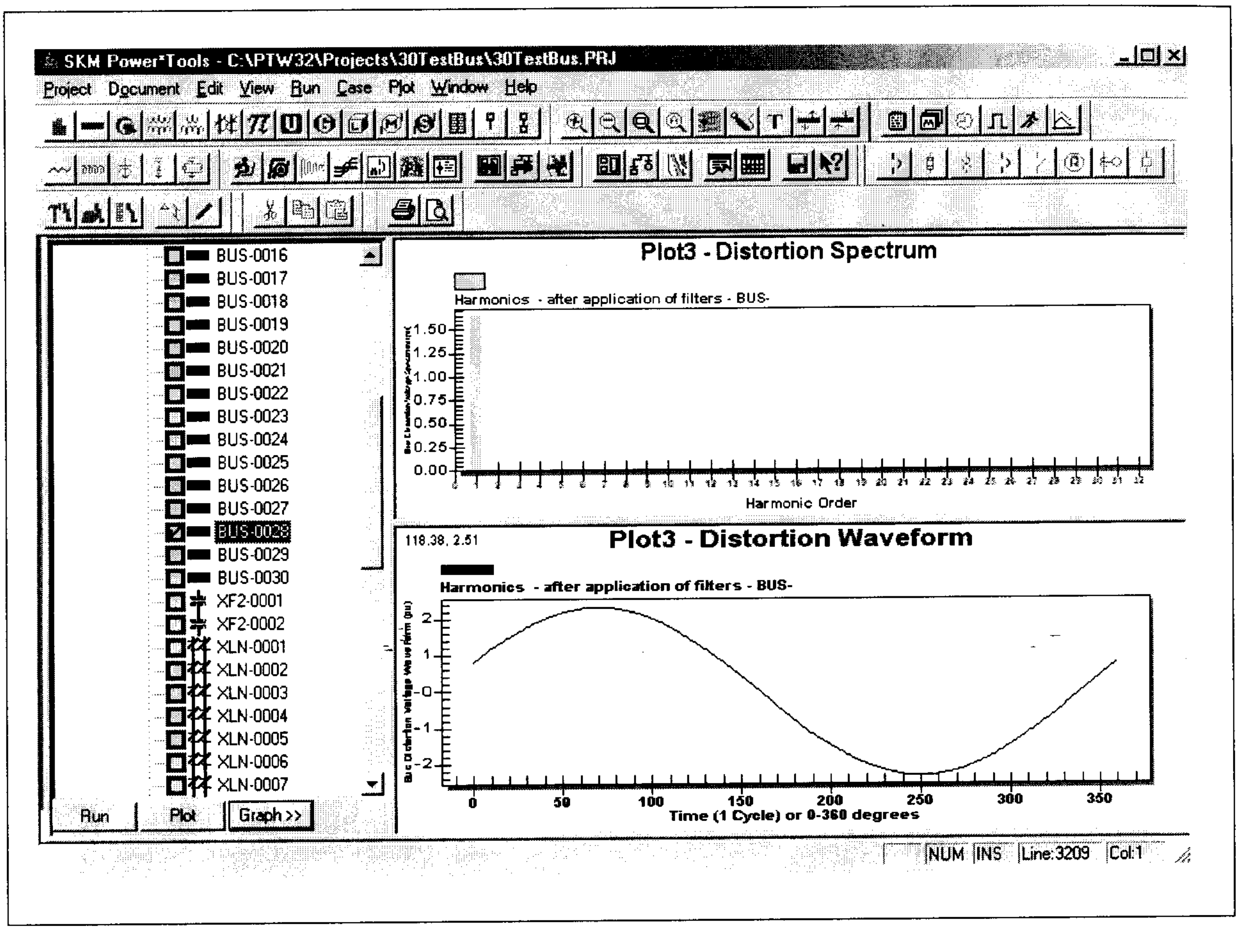


Figure G-3. Distortion waveform and spectrum at bus-0028 after application of filters.

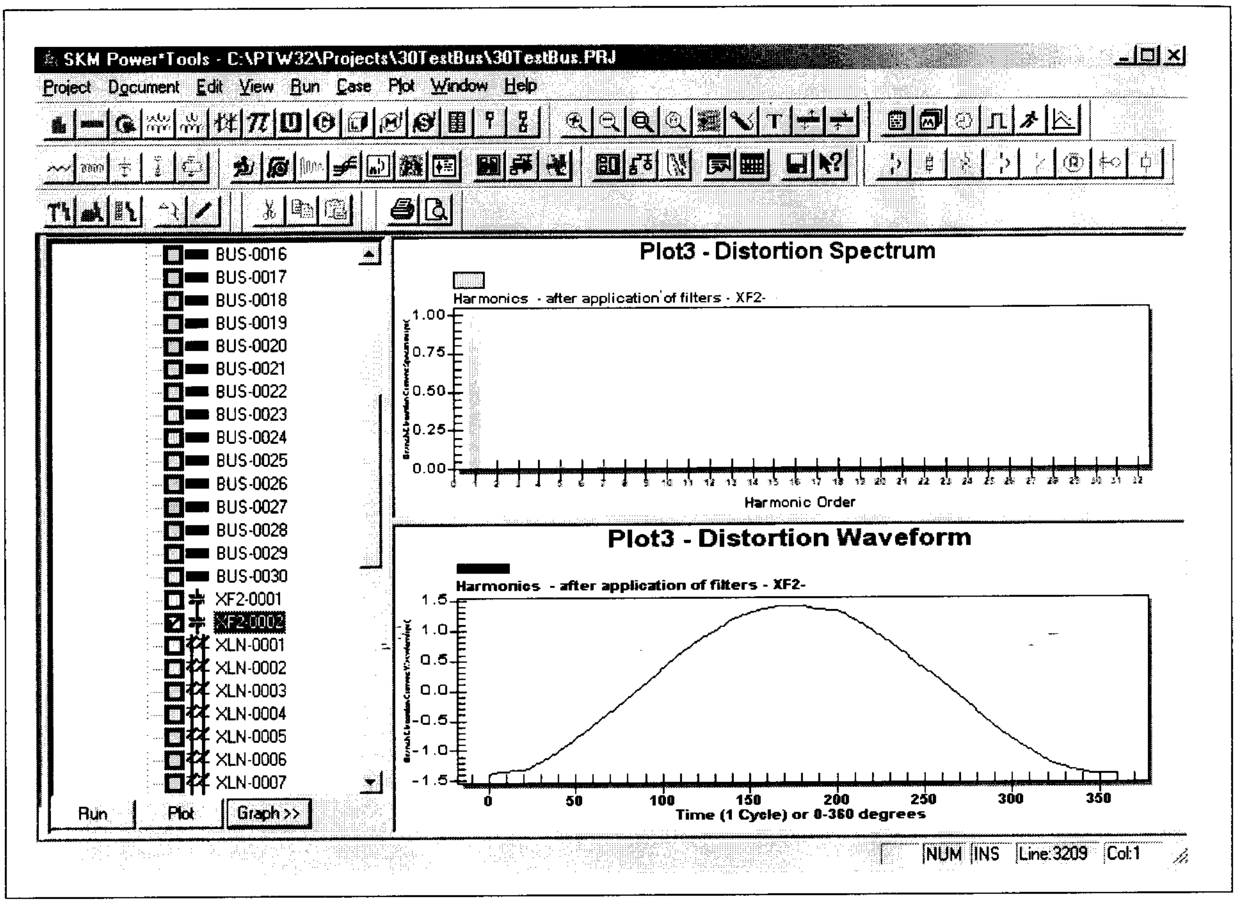


Figure G-4. Distortion waveform and spectrum at Trf-0002 after application of filters.

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